

Draft

Appendix E

Pluto-Kuiper Express

Mission and Project Description

APPENDIX E

PLUTO-KUIPER EXPRESS MISSION AND PROJECT DESCRIPTION

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APPENDIX E

PLUTO-KUIPER EXPRESS MISSION AND PROJECT DESCRIPTION

1. Introduction

This appendix provides background information about the Pluto-Kuiper Express mission and pointers to the present body of relevant scientific knowledge. This information is to be used in conjunction with Appendices A and D by proposers in preparing a formal response to NASA AO 99-OSS-XX, Outer Planets Program Announcement of Opportunity.

This document contains general information, requirements, technical descriptions, and performance and interface envelopes that are pertinent to the preparation of proposals in response to the Pluto-Kuiper Express part of the AO. Also given is a detailed description of the activities for which the selected Principal Investigators (PI's) will be responsible. Information from the AO is repeated only if necessary for continuity of content. In the event of conflict between the provisions of the AO and any appendix, the AO takes precedence.

It is important to note that the reference mission described here is only one of several options under study. The AO which this appendix accompanies will result in the selection of a Pluto Remote Sensing Science Investigation and a Pluto Radio Science Investigation, the leaders and members of which will become members of the Pluto-Kuiper Express Integrated Implementation Team. This team will select the final mission design.

The science investigations proposed by the winning teams, as well as the reference mission described in this appendix, will evolve together into an end-to-end mission that best meets the science objectives within the strict cost cap. The actual Pluto-Kuiper Express mission that is implemented may differ substantially from the reference mission and the details of the winning science investigation proposals.

NASA has not committed to this project, nor this reference mission, nor to any specific launch schedule, launch vehicle, power system, Project budget, or funding profile.

The word "mission" means the Pluto-Kuiper Express mission. "Spacecraft" is synonymous with "flight system" including all launched hardware and software. The word "Pluto" may be used to refer either to the planet itself or to the Pluto-Kuiper Express mission (as in "...will be developed for Pluto"). The word "project" is used in this document to refer to the Outer Planets/Solar Probe Project. The word "investigation" will be used to refer to a science investigation under a Principal Investigator (PI) chosen through this AO, and is inclusive of all factors under the purview of the PI. "Science payload" or "payload" refers to the hardware and software flight elements of an investigation.

2. Overview

2.1 Science Objectives

2.1.1 Mission Overview

The Pluto-Kuiper Express mission is designed to provide the first reconnaissance of the Solar System's most distant planet, Pluto, and its moon Charon. Recent progress in understanding Pluto and Charon enabled a well-focused set of questions to be developed that can be addressed by a first spacecraft reconnaissance of the system. Fundamental questions regarding the physical and chemical processes in protoplanetary disks and their relationship with the surrounding nascent molecular cloud will be addressed through study of Pluto and Charon. Analysis of the cratering and tectonic records of these bodies will enable an investigation of the environment of the outer Solar System during its early history. The physics of the unique evolution of Pluto's atmosphere as the planet moves away from the Sun will also be a focus of study on this mission.

The reference mission calls for a single spacecraft on a flyby trajectory of the Pluto/Charon system. The spacecraft will carry an integrated array of scientific sensors, including radio science, which will satisfy at least the Group 1 objectives developed by the Outer Planets Science Working Group and described in Section 2.1.2. Radio science provides an essential complement to fulfill these goals, and the required PI-provided hardware will be incorporated as part of the spacecraft subsystems. Two science investigation teams will be competitively selected: one for optical remote sensing science and one for radio science. The selected teams will be expected to work closely with spacecraft designers and each other to produce an integrated spacecraft within the stringent cost, mass, power, and mission design constraints of the mission.

The recent discovery of dozens of objects, from comet-sized up to hundreds of kilometers, orbiting in the predicted Kuiper Belt region just beyond the known planets, has raised the exciting possibility of an extended mission to fly close to one or two such bodies. If remaining spacecraft resources permit, the mission may be extended to explore the Kuiper Belt. If implemented, this extended mission would allow comparison of the properties of Pluto and Charon with the smaller bodies from which they (and the larger outer planets) were likely assembled.

2.1.2 Science Objectives.

The Outer Planets Science Working Group carefully considered the range of science objectives appropriate to a first reconnaissance mission to Pluto. These were then prioritized, and their final ranking, endorsed by the Solar System Exploration Subcommittee, appears below.

Group 1 objectives are considered absolutely essential to the first-scientific reconnaissance mission; Group 2 objectives are considered important but not mandatory; Group 3 objectives are considered desirable but secondary.

The groupings resulted in a scientifically compelling set of focused goals for a first reconnaissance:

Group 1 Objectives:

- Characterize the global geology and morphology of Pluto and Charon;
- Map surface composition of Pluto and Charon; and
- Characterize the neutral atmosphere of Pluto and its escape rate.

Group 2 Objectives:

- Characterize the time variability of Pluto's surface and atmosphere;
- Image Pluto and Charon in stereo;
- Map the terminators of Pluto and Charon with high resolution;
- Map the surface composition of selected areas of Pluto and Charon with high resolution;
- Characterize Pluto's ionosphere and solar wind interaction;
- Search for neutral species including H, H₂, HCN, and C_xH_y, and other hydrocarbons and nitriles in Pluto's upper atmosphere, and obtain isotopic discrimination where possible;
- Search for an atmosphere around Charon;
- Determine bolometric bond albedos for Pluto and Charon; and
- Map the surface temperatures of Pluto and Charon.

Group 3 Objectives:

- Characterize the energetic particle environment of Pluto and Charon;
- Refine bulk parameters (radii, masses, densities) and orbits of Pluto and Charon;
- Search for a magnetic fields from Pluto and Charon; and
- Search for additional satellites and rings.

2.1.3 Measurement Requirements

In this section we list, by science area, measurement objectives for science sensors, or in cases where appropriate, the slightly looser "goals" for sensor capability in order to meet the Group 1 objectives given above. Some investigations may have the capability to also meet other objectives in Groups 2 and 3.

2.1.3.1 Geology and Geomorphology

Panchromatic mapping: Obtain panchromatic viewable disk coverage of both Pluto and Charon at a resolution of 1 kilometer per line pair (1 km/lp), or equivalent. The 1 km/lp objective is to be obtained at the subspacecraft point; it is understood that a combination of image projection effects and spacecraft data storage limitations may degrade resolution away from the subspacecraft point.

Color mapping: Obtain viewable disk coverage of both Pluto and Charon in 2 to 5 color bands at a resolution of 3-10 km/lp (or equivalent). The resolution requirement is to be obtained at the subspacecraft point; it is understood that a combination of image projection effects and spacecraft data storage limitations may degrade resolution away from the subspacecraft point.

Phase angle coverage: Obtain sufficient imaging at moderate and high phase angles to specify the phase integrals of Pluto and Charon.

Image dynamic range and signal-to-noise ratio (S/N): For all imaging, provide sufficient dynamic range to cover brightness contrasts of up to 30 (i.e., normal albedo between 0.03 and 1) with an average S/N goal of about 100, but somewhat lower S/N in the darkest regions.

2.1.3.2 Surface Composition Mapping

Mapping coverage, resolution and sensitivity: Obtain infrared spectroscopic maps of one hemisphere of both Pluto and Charon with approximately 10 km/pixel resolution at disk center. Be able to detect a < 0.02 change in albedo everywhere in the spectrum.

Goal for compositional determination: Using the techniques of quantitative near-infrared spectroscopy, determine the spatial distribution and crystalline phases (i.e., or) of frozen N₂ and secondary constituents such as CO, CH₄. Determine quantitatively the presence of such additional major exposed volatiles, hydrocarbons, and minerals (or rocks) as may exist, all at spatial resolution of 5-10 km/pixel or equivalent.

Spectral coverage and resolution: For each spatial resolution element, obtain a spectral resolution ($\lambda/\Delta\lambda$) of at least 250 per pixel over all or part of the 1 - 5 micron region (or beyond, if relevant).

2.1.3.3 Neutral Atmosphere Characterization Composition

Determine the mole fractions of N_2 , CO , CH_4 and Ar in Pluto's atmosphere to at least the 1% level. Composition of any constituents below this level (minor constituents) is a Group 2 science objective.

Thermosphere thermal structure: Measure T and dT/dz at 100 km vertical resolution to 10% accuracy at gas densities of 10^9 cm^{-3} and higher. Aerosols: Characterize the optical depth and distribution of near-surface haze layers over Pluto's limb at a vertical resolution of 5 km or better.

Lower atmospheric thermal structure: Measure T and P at the base of the atmosphere to accuracy's of $\pm 1 \text{ K}$ and $0.1 \text{ } \mu\text{bar}$.

Evolution : Determine the atmospheric escape rate.

2.1.4 Strawman Payload

The strawman payload developed by the Outer Planets Science Working Group is designed conceptually to meet all of the Group 1 science objectives. It is comprised of an integrated ultraviolet, visible, and infrared remote sensing package, plus a radio science experiment. In this strawman, neither the technique nor the architecture of the integrated package is described; all that is provided is a guide to how the investigation *could* respond to the science objectives through the use of instruments with particular choices of wavelength range, sensitivity, and resolution (spatial and spectral). We discuss the radio investigation in more detail because of its intimate and potentially complex relationship to the spacecraft telecommunications subsystem.

2.1.4.1 Visible Imaging

The Pluto Express visible wavelength images of Pluto and Charon will permit geological mapping of surfaces and will contain important insights into the formation, evolution, and composition of the system. Surface albedo variations that are seen in ground data and Hubble images will be resolved into regions of differing terrain or composition. Images of Pluto will likely reveal deposits of ice, which will help to understand the atmosphere and its interaction with the surface during its seasonal cycle of sublimation and condensation. Cratered

areas will provide insight into the impactor flux at the edge of the Kuiper Belt, as well as provide relative ages of surfaces. Large scale morphologic features will inform us of the thermal and geologic history of Pluto's crust.

Two categories of visible images of Pluto and Charon form the primary data set required to support the science objectives. These are 1) multispectral images with 5-10 km resolution in several (i.e., two to five) wavelength bands chosen to provide compositional information, and 2) high-resolution panchromatic images (1 km/lp at subspacecraft point) of the full disk to provide information on surface structures.

Other image data that can be obtained by the visible image, contingent on the design, are:

1. Images of selected surface regions at higher resolutions;
2. Observations of atmospheric aerosols in forward scattered light;
3. Data taken over a range of phase angles;
4. Selected stereo pairs; and
5. Images of the space surrounding Pluto to search for small satellites.

2.1.4.1.1 Optical Navigation Requirements

The science visible imaging camera is planned to also be used for navigation imaging. For purposes of optical navigation, the encounter phase of the mission starts when Pluto subtends more than one pixel (approximately one year before Pluto encounter, depending on the imaging system design).

The fundamental requirement is to be able to image Pluto together with at least 2 well-placed reference stars in an unsmear exposure. To insure adequate probability of capturing the planet and neighboring stars in images during Pluto approach given spacecraft pointing uncertainties, the FOV is required to be 7 mrad in both directions. Because of the critical importance of successful optical navigation to Pluto mission success, the visible camera shall be made block-redundant against all credible inflight failures.

The camera requirements on FOV and angular pixel size will determine the degree to which pointing errors to Pluto at closest approach can be reduced via optical navigation. A reasonable pointing update strategy assumes that the last onboard update to the pointing and timing of the closest approach observing sequence is based on a final observation made at E-4 hours. Figure 1 shows the closest approach 3 pointing error (residual navigation error root sum squared with spacecraft pointing error) as a fraction of the camera FOV in the along-track direction vs. the Pluto flyby distance for various assumptions regarding the camera FOV and angular pixel size. Proposers may trade among these parameters in such a way as to maximize science return taking into account the limitations of the optical navigation accuracy implied.

This plot assumes that planet center-finding errors will limit the best achievable uncertainty in Pluto closest approach time to ~ 2 sec (1 σ). Larger format arrays will allow closer flybys with the same pointing update scenario and residual fractional-FOV pointing error. The limiting flyby distance is reduced by the square-root of the increased array size factor. Other pointing update scenarios that use later optical navigation information would allow even closer flybys, while maintaining a given fractional-FOV navigation-induced pointing error at closest approach.

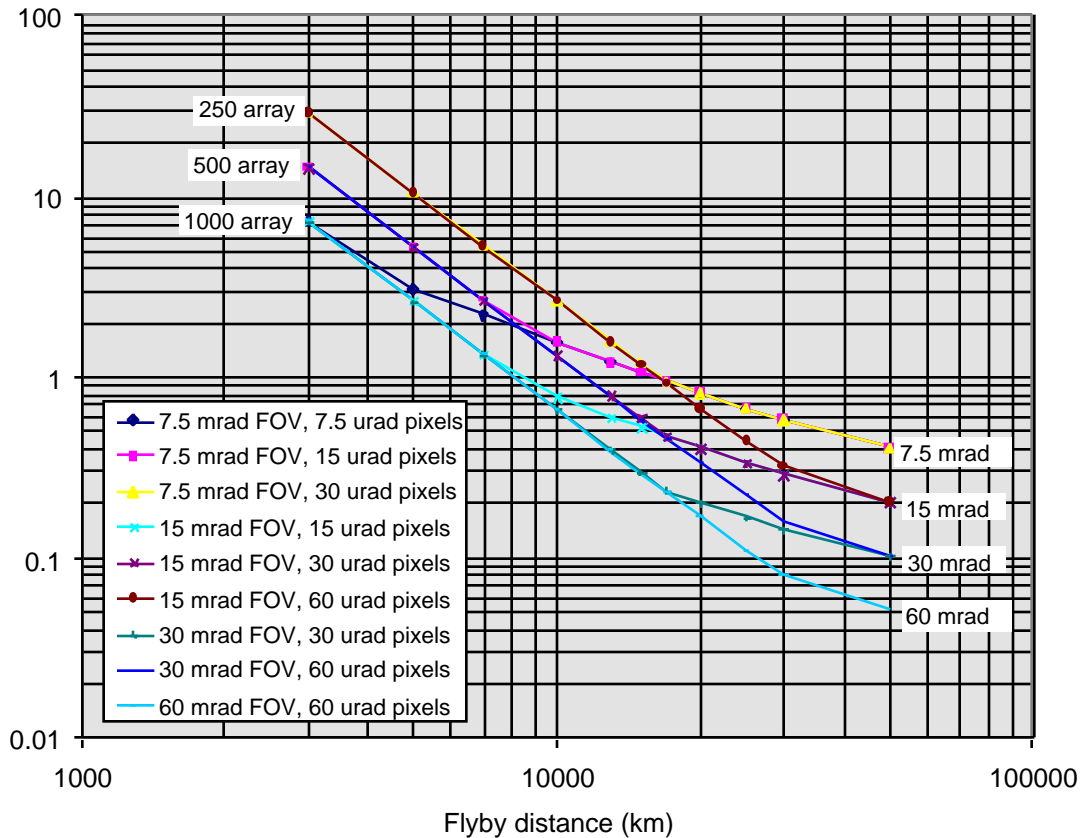


Figure 1. Fractional FOV pointing error (3 σ) at Pluto closest approach in the along-track direction as a function of flyby distance, camera FOV, and angular pixel size. This error includes both spacecraft pointing control error and residual uncertainty in the time of closest approach using the best available optical navigation data up to E-4 hours.

The required star image centroiding accuracy requires that the camera's point spread function have a full width at half maximum of ≤ 1 pixel so that the star images are sufficiently spatially sampled. Any geometric distortion in the images must be correctable onboard to ≤ 0.1 pixel, and the maximum change in geometric distortion over a 30-day period must not exceed 0.1 pixel.

The minimum signal-to-noise ratio (SNR) for the central pixel in a star image must be ≥ 7 in images for which smear is kept to ≤ 1 pixel. For a spacecraft pointing stability capability of $10 \mu\text{rad/sec}$, the maximum allowable exposure time is given by $p/10 \mu\text{rad/sec}$, where p = the angular pixel size; e.g., for $p = 20 \mu\text{rad}$, the maximum exposure time is 2 sec. Spatially-resolved Pluto must not generate a signal that exceeds the full-well or maximum encoded level of the detector in the same frame that meets the star SNR requirement.

For the apparent galactic latitude of Pluto, Figure 2 shows the limiting stellar magnitude for which at least two stars brighter than the limiting magnitude can be expected within the indicated camera FOV. Camera sensitivity must be great enough to insure that stars of the indicated limiting magnitude will generate peak SNR values ≥ 7 for the maximum allowed exposure time. Figure 3 shows the required minimum ratio between the detector's full-well level and its read noise floor to insure that at least two stars with peak SNR ≥ 7 and an unsaturated Pluto can be captured in a single frame as a function of the camera FOV for selected detector array sizes. Camera sensitivity, FOV, angular pixel size, noise floor, and full well can be traded off within the limits defined here.

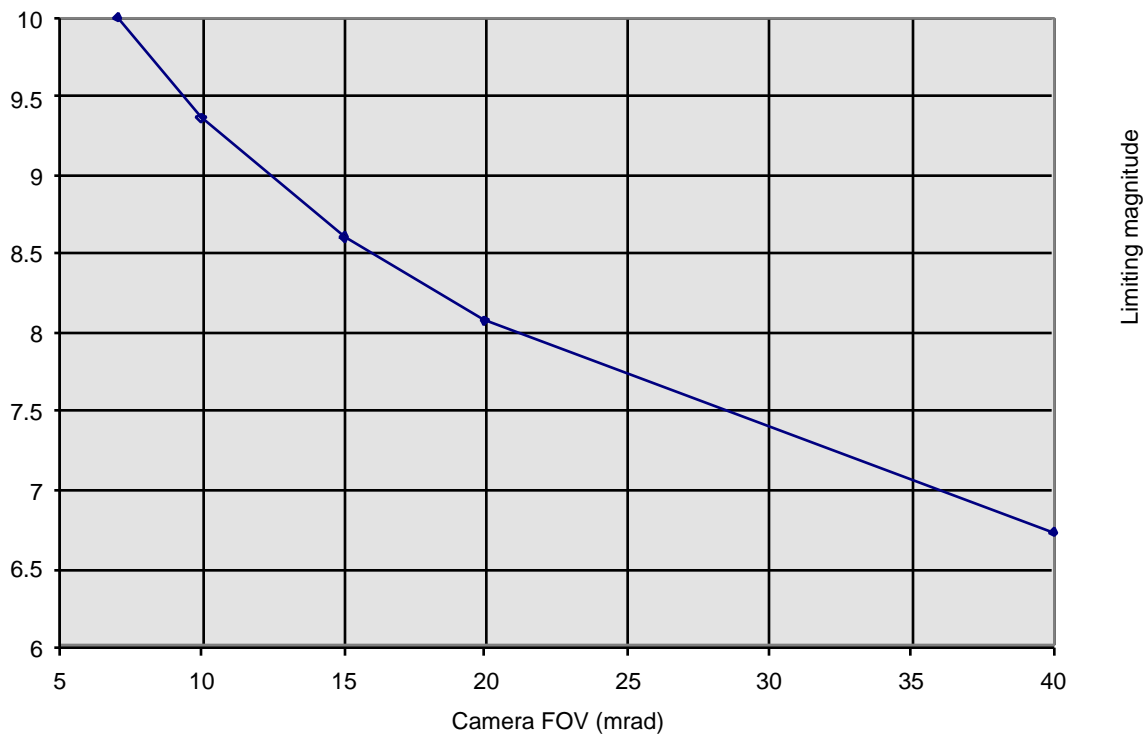


Figure 2. Limiting stellar magnitude for which at least two stars of that magnitude or brighter will be contained in the indicated FOV.

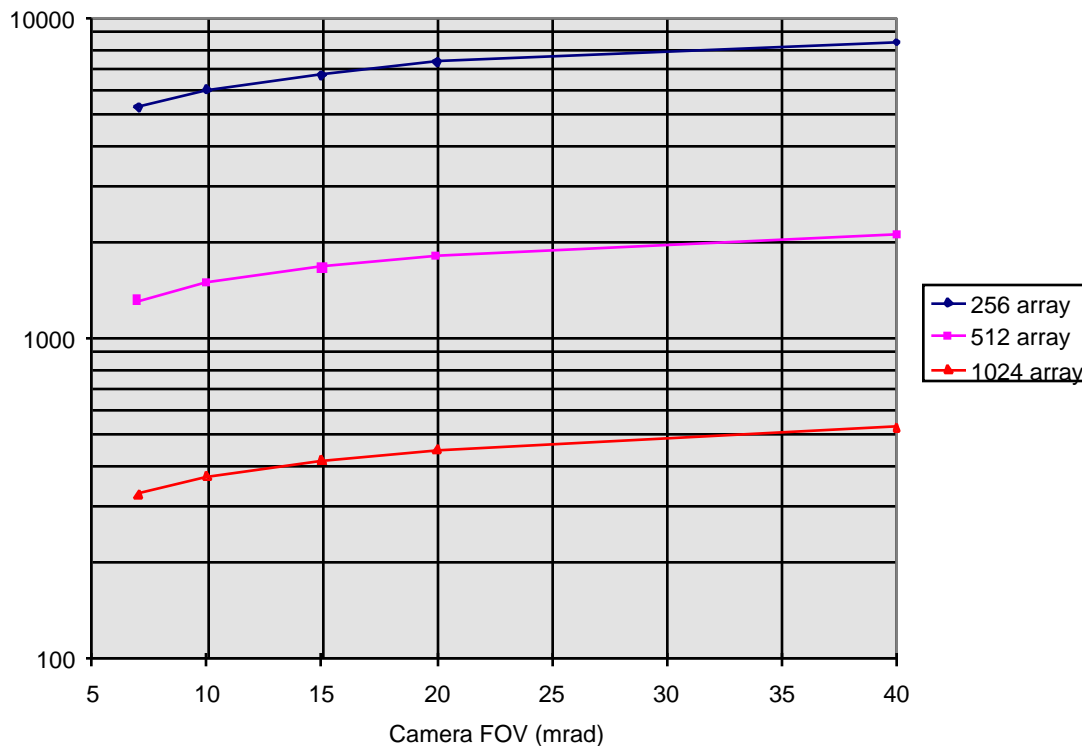


Figure 3. Minimum ratio of detector full well level to its read noise floor required to capture at least 2 stars with peak SNR = 7 and an unsaturated Pluto in the same frame as a function of the camera FOV for selected detector array sizes.

2.1.4.2 Infrared Mapping Spectroscopy

The Infrared Spectral Mapping component would determine the surface compositions of Pluto and Charon by performing spectroscopic mapping in the near infrared. Spectral features of interest are distributed through the wavelength range between 1- 5 microns. Quantitative measurements will be made of exposed volatiles, hydrocarbons, and minerals. On approach, maps of the sunlit sides of both Pluto and Charon would be recorded at high spatial resolution. The spectral resolution ($\lambda / \Delta\lambda$) required is about 250 per pixel. The infrared imaging format should permit full disk mapping with spatial resolution better than 10 km per pixel. The spacecraft rate control must be considered in the instrument design, if long integration times are required to achieve an acceptable signal-to-noise ratio.

2.1.4.3 Ultraviolet Spectroscopy

The goal of this component is to measure the composition and structure of the neutral atmosphere by studying Pluto's airflow and detecting spectral absorption features during solar occultation; the general wavelength region of interest is 50-200 nm. This portion of the remote sensing investigation would be designed to meet the neutral atmosphere structure and composition objectives except for measurement of temperature and pressure near the surface. Sufficient sensitivity, spectral resolution, and spectral coverage are required to measure the mole fractions of N_2 , CO , and CH_4 with a vertical resolution of 100 km to a 10% accuracy for atmospheric densities exceeding 10^9 cm^{-3} . Since it will be required that the high-gain antenna be pointed at Earth beginning shortly before and after Earth occultation, and since the Earth and Sun occultations overlap in time, it will be necessary for the UV solar occultation experiment to make design provisions to view the Sun while the high-gain antenna is pointed at Earth. In the strawman payload, this is accomplished by means of a small viewing port in the antenna. The UV FOV will need to be 4° to cover the possible range of angles between the Earth and Sun during the occultations.

2.1.4.4 Radio Science Investigation

The Radio Science occultation will measure the vertical structure of Pluto's atmosphere by sensing the phase retardation of the radio signals imposed by the neutral gas during Earth occultation immersion and emersion. This experiment is expected to meet the neutral atmosphere objective of determining the surface temperature and pressure. In addition, the atmospheric structure for several scale heights above the surface will be determined so that a broad picture of the factors and processes controlling the atmosphere in the vicinity of the Pluto's surface can be developed.

Estimates of the surface pressure of Pluto range between roughly 3 and 50 microbars (μbars), but the uncertainties are essentially unknown. Consequently, it is prudent to consider the lower value as an upper bound for the design of any occultation observation. Meaningful measurements will require sensitivities adequate to characterize accurately an atmosphere in the range of 1 μbar . One approach to estimation of the expected effects is to scale observed values from the *Voyager* Triton occultation to the Pluto case. This results in an expected observable phase shift of a surface occultation ray at Pluto in the range of 0.12 radians/ μbar . From these considerations, it is clear that stable measurements of phase with accuracy's in the range of 0.01 radian (0.5 degrees) will be required, and the radio occultation should yield the atmospheric structure for pressures greater than about 1 μbar . In particular, for the nominal surface pressure of 3 μbar the temperature and pressure both should be obtained to a few percent. The observations should provide adequate signal-to-noise ratio to support the

objectives, and a sufficient sampling rate to determine the position of the surface to within approximately 100 m radius relative to the atmospheric profile and the navigation trajectory solution.

As a Group 2 objective, the ionosphere of Pluto also would be sensed by the same experiment; measurements should begin above the highest expected ionosphere to avoid contamination of the neutral atmospheric data by uncalibrated ionosphere effects and to obtain the ionosphere profile.

While the neutral atmosphere of Charon is not thought to be sensible by radio occultation, a possible ionosphere of Charon is also of interest and should be accessible to radio occultation observations. It may be possible to accomplish a near occultation of either Pluto or Charon, followed by a distant occultation of the other. The occultations are expected to be rapid, with the vertical component of the ray path velocity in the range of 3.5 km/sec as determined by the characteristics of flight times. While conditions will be somewhat different for different trajectory options, there will be essentially no opportunity to adjust the trajectory for occultation purposes other than by choice of the asymptotic aim point.

The investigation design goal is to integrate as much of the Radio Science instrumentation as possible with the spacecraft telecommunications subsystem in order to improve total mass, power, operability, and cost of the spacecraft and sensors, while maintaining the investigation's capability to address the science objectives.

The Pluto Express telecommunications subsystem is planned to operate uplink at X-band (7.1 GHz, 4.2 cm) and downlink at X-Band (8.4 GHz, 3.6 cm). While some change may be expected as the spacecraft design process advances, the spacecraft antenna is expected to be 2-m diameter, and the downlink transmitter power will be in the range of 5 to 20W (X-Band). The spacecraft will be commanded through NASA Deep Space Network facilities, nominally radiating 20 kW from 34-m diameter ground antennas. The ratio of received carrier power to noise spectral density is expected to be in the neighborhood of 44 dB Hz. The planned spacecraft transponder will be capable of deriving its downlink signal either from an onboard oscillator or from the uplink signal when an uplink is present. There would be no mission engineering requirement to carry a highly stable onboard frequency reference, but it is planned that the radio design will permit use of such a device were it to be required by a radio science investigation. At Pluto range, the downlink signal-to-noise ratio received on the ground from the spacecraft transmitter is expected to be too low to satisfy the Pluto atmospheric objectives.

Current plans call for the Telecommunications Subsystem to use the Small Deep Space Transponder (SDST), which has design provisions specifically to accommodate uplink Radio Science experiments. The envisioned PI-supplied radio science hardware consists of an ultrastable oscillator and a signal processing unit. The SDST will accept reference input from an Ultrastable Oscillator at 76 MHz, allowing for stable down-conversion in the receiver module and for stable clock generation. In the uplink Radio Science mode, the receiver operates with fixed gain selectable from seven settings, from -18 to +15 dB. Analog to digital conversion at baseband is done in the transponder. I and Q channels, within a ± 5 kHz bandwidth centered on the carrier, are output from the SDST to the signal processing unit through a special radio science interface. This is a serial interface consisting of a radio science data output, radio science clock output, and radio science enable output; its electrical characteristics conform to the standard RS-422 requirements.

Two data words are provided, I and Q, each consisting of 14 bits. The serial data is clocked out of the SDST using a 4-MHz clock. The clock is provided as a burst of 28 pulses with the data changing on each clock falling edge. The enable signal envelopes the data and clock burst. The least significant bit of the I channel, I₀ is shifted out first. The last bit shifted out is the most significant bit of the Q channel, Q₁₃. The 28 bit burst occurs every 10 microseconds (100 kHz). The signal processing unit generates reduced data for downlinking at a very modest rate.

Some pertinent performance specifications on the SDST follow. The carrier track threshold of the receiver is expected to be about -156 dBm. In the open-loop, fixed gain operational mode, receiver gain will not vary more than 0.1 dB over any ten minute period. The receiver may not degrade the stability of the USO reference signal, as characterized by Allan deviation, by more than 10% over a 20-minute observation time.

2.1.4.5 Particles and Fields

There is no particles/fields instrument/integrated package *per se* included in the strawman payload developed by the Outer Planets Science Working Group or the Science Definition Team. Particles and fields investigations are not considered part of the Group 1 objectives, and the reference spacecraft is not designed to accommodate particles and fields experiments. If proposers choose to include a fields and particles experiment in their integrated science investigation, any necessary modifications to the spacecraft and mission should be taken into account.

2.2 Description Of Spacecraft Concept And Mission

2.2.1 Reference Mission

What follows is the description of a "reference mission," giving a snapshot of current thinking at the time this AO was in preparation. Because the Outer Planets/Solar Probe Project is still in early definition, many important details remain to be worked. In fact, major aspects of the entire mission architecture may be changed and improved as a result of the spacecraft and mission development process in which the selected science investigation teams will become major participants. Only then will a baseline mission be determined and the design of all its elements be brought to closure and implemented. The information that follows is intended to provide proposers with a point of common reference and some insight into results of developments that have taken place to date.

Although the reference mission launch date is December 2004, the option exists to launch in November 2003 if the necessary Europa Orbiter technology development is delayed so as to preclude its launch in 2003. Europa technology readiness decision points are scheduled for October 1999 and October 2000, and the Pluto launch date could be advanced to 2003 at either of these decision points.

2.2.1.1 Baseline Mission

The reference Pluto-Kuiper Express (Pluto) mission calls for a launch in December 2004 and uses a Jupiter Gravity Assist (JGA) trajectory to send the spacecraft to Pluto and Charon (see Figure 4). The launch vehicle may be either the STS/IUS or Delta III class both with an additional Star-48V kick-stage. The performance of these launch systems, in conjunction with the estimated spacecraft system mass, results in a flight time to Pluto of 8 years. Figure 4 below illustrates the geometry and key dates of the 2004 JGA trajectory for the Pluto mission (the 2003 interplanetary trajectory would look similar). The opportunity to switch the launch order of the Pluto and the Europa Orbiter mission, however, is a key requirement of the program readiness strategy. If the option to switch the Pluto and Europa Orbiter launches is exercised, the Pluto launch would then be moved up to November 2003, and Europa Orbiter would move into the December 2004 slot. The 2003 JGA provides somewhat better launch vehicle injection capability for the same flight time as the 2004 JGA. Figure 5 below shows the flight system mass versus flight time to Pluto for both the 2003 and 2004 JGA trajectory opportunities.

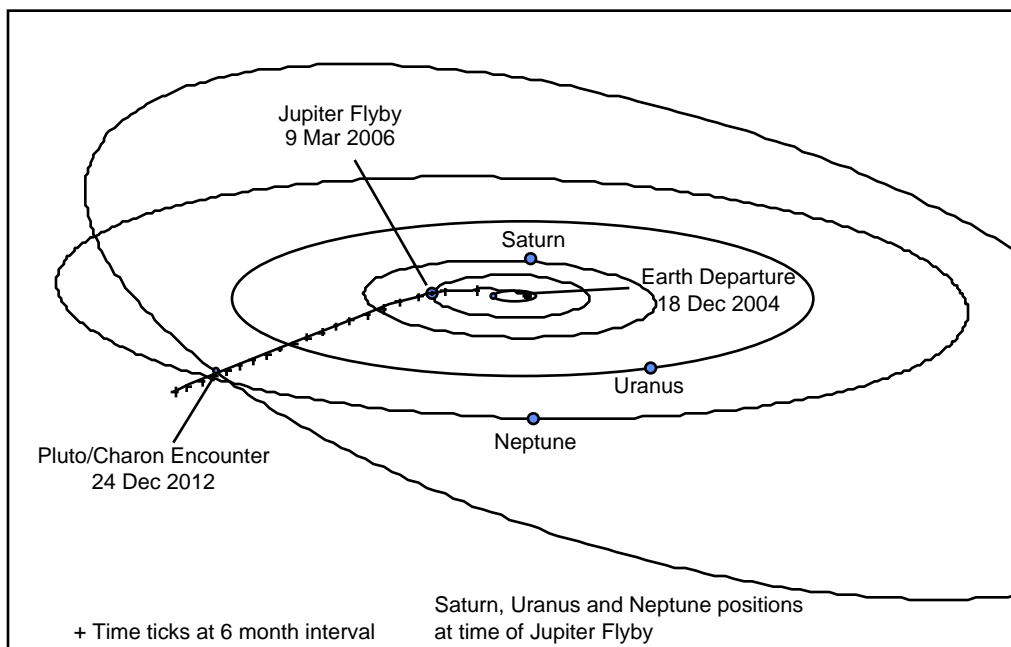


Figure 4. Pluto-Kuiper Express 2004: 8-year JGA trajectory.

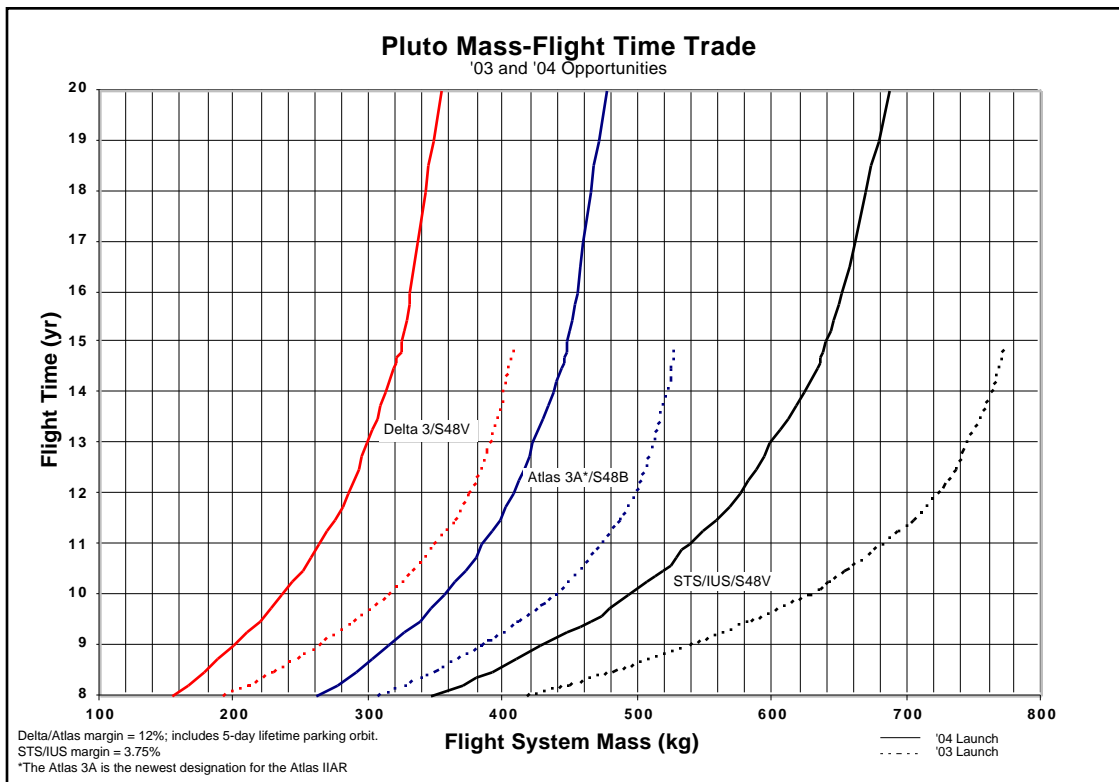


Figure 5. Relationship between flight time to Pluto and flight system wet mass

Figure 6 below shows the spacecraft trajectory through the Jovian system for the baseline Pluto mission. The flight time determines the conditions of the JGA, the most important of which to the spacecraft is perijove radius. Figure 7 below illustrates the change in the spacecraft's perijove radius with respect to flight time for both the 2003 and 2004 JGA trajectories. This effect on flyby radius at Jupiter has a significant impact on spacecraft radiation exposure from the intense environment at Jupiter as the spacecraft passes through the Jovian system, as is also illustrated in Figure 7.

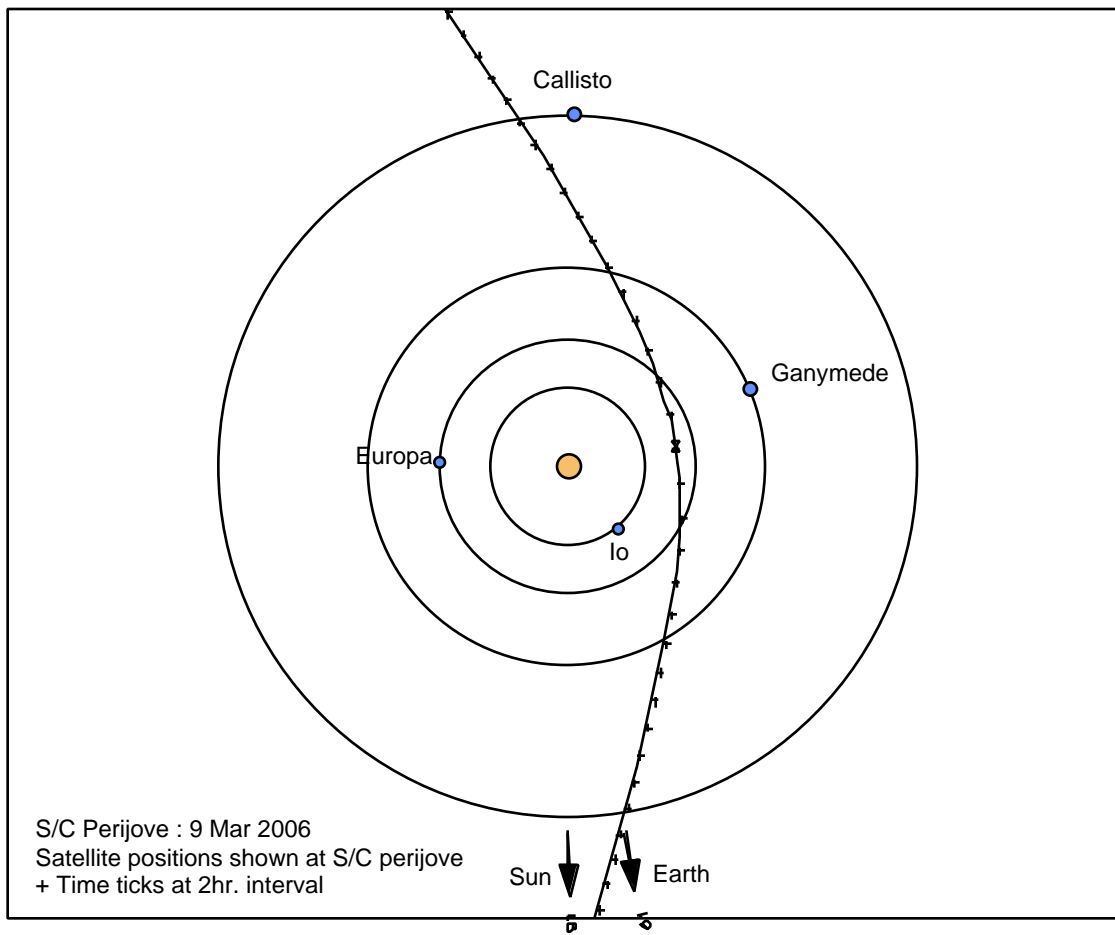


Figure 6. Pluto-Kuiper Express 2004 : Jupiter flyby, 8-year JGA trajectory.

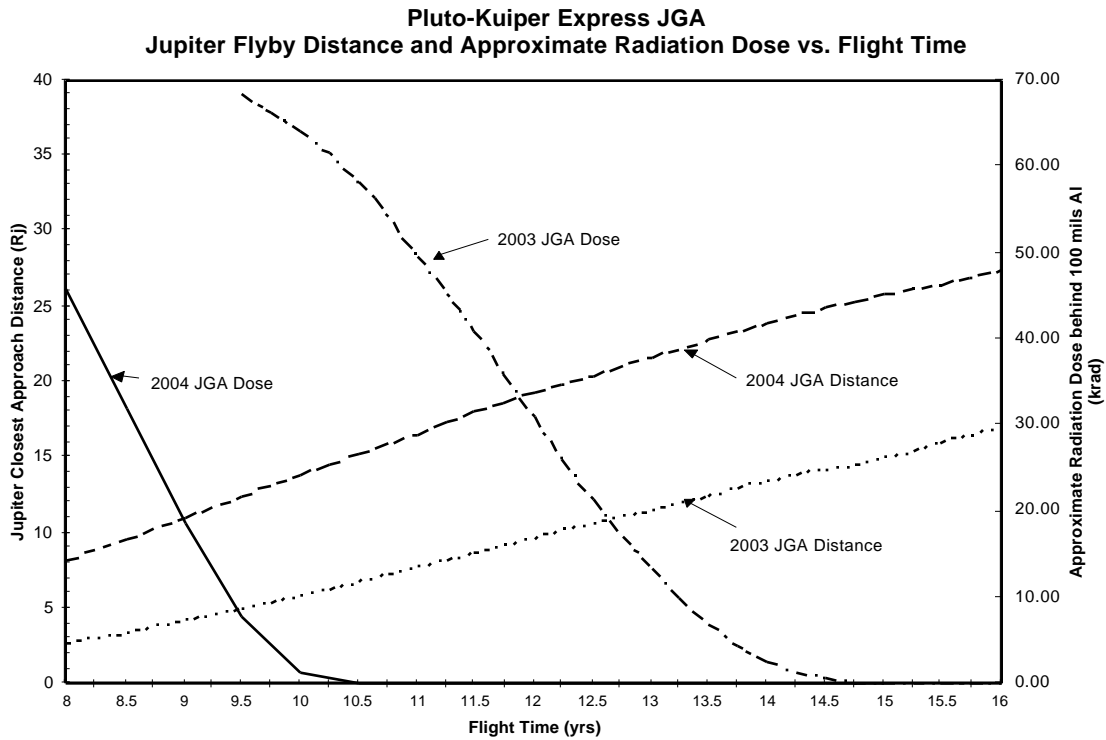


Figure 7. Perijove radius vs. flight time vs. radiation dose for 2003 and 2004 JGA.

As one might expect, the flight time also impacts the Pluto flyby itself. Figure 8 below shows the incoming hyperbolic excess speed, V_{∞} , at Pluto versus flight time for both the 2003 and 2004 JGA trajectories. This translates directly into how fast the spacecraft passes through the Pluto/Charon system. As Figure 8 shows, as the flight time increases, the V_{∞} at Pluto decreases. This clearly has an impact on the entire Pluto - Charon encounter scenario, particularly in the timing of science data collection as well as the constraints on the spacecraft and instruments in terms of slewing, stability, etc.

Figure 8 also shows that approach phase angle varies as flight time varies from 8 to 16 years. The amount of Pluto's surface in continuous winter night also increases as the arrival date at Pluto is postponed (see Figure 9).

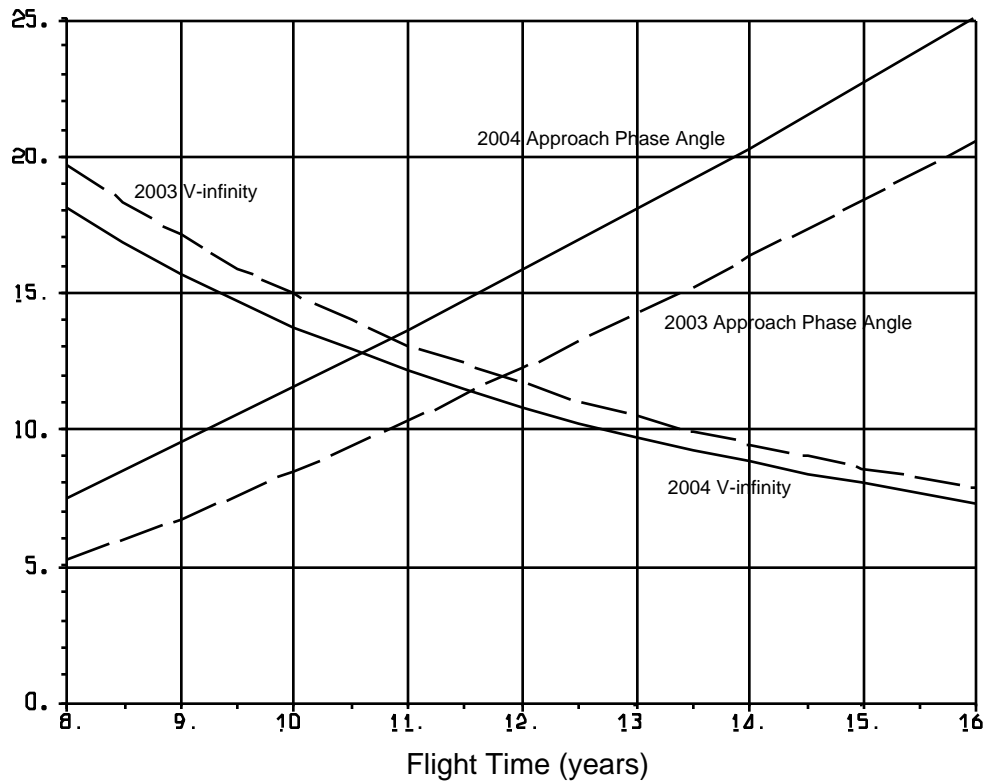


Figure 8. Pluto V_{inf} and approach solar phase angle as a function of time

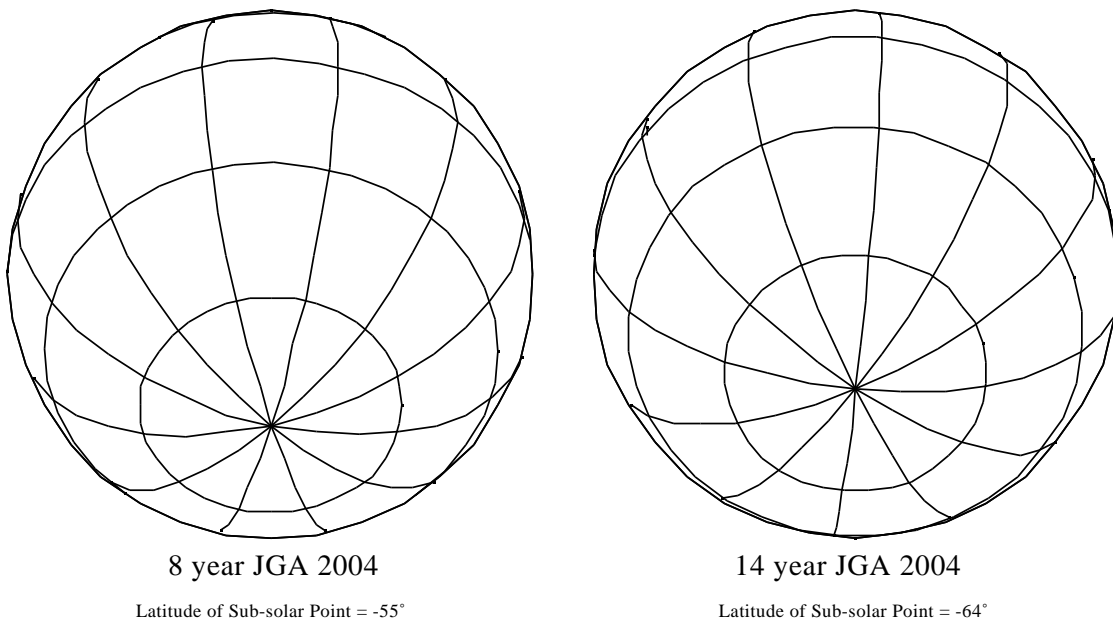


Figure 9. View from Sun at Pluto arrival

Table 1. Pluto/Charon encounter trajectory characteristics - 2004 JGA 8 yr. trajectory.

	Pluto	Charon
Date of Encounter	December 24, 2012	
Solar Distance (AU)	32.36	
Time of Closest Approach	05:30:51	05:38:24
Closest Approach Range (km)	11,308	28,628
Closest Approach Relative Velocity (km/sec)	18.21	18.43
Aim Point*: BT, BR (km)	-7,442.8, 8,517.3	-21,843.7, 18,506.4
Solar Occultation Start	06:43:48	08:55:58
Solar Occultation End	06:54:30	09:05:50
Earth Occultation Start (SCET)	06:42:28	
Earth Occultation End (SCET)	06:57:02	

Note: All time provided in Ephemeris Time, except as indicated.

* Provided in Earth Ecliptic and Equinox coordinates of J2000

2.2.1.2 Other Options for the Mission Design

As stated above, the nominal Pluto mission makes use of the 2004 JGA launch opportunity. Although launch opportunities to Jupiter exist roughly every 13 months, the planetary phasing is such that after 2004, Jupiter is no longer in position to support a JGA to Pluto until 2015 and 2016. At present there are no backup missions under consideration.

2.2.1.3 Pluto Encounter Geometry Description

The spacecraft approaches the Pluto/Charon system with a relative speed of about 18 km/sec. At this speed, the close encounter spans only a few hours. Optical navigation, in concert with radiometric navigation, will reduce the time of flight error to a few seconds at Pluto closest approach. Automated onboard optical navigation in the last few hours before closest approach enables this accurate timing.

The selection of the Pluto encounter aimpoint is driven by the goal to obtain both Sun and Earth occultations of Pluto as well as a Sun occultation of Charon. It is also desirable, for obvious reasons, for the spacecraft closest approach to Pluto to be as small as possible, within the navigation and spacecraft (including science instrument) design limitations. The geometry of the flyby, as noted earlier, is driven primarily by the flight time. The encounter

scenario must take this geometry into account to find the best way to satisfy all principal science objectives. Table 1 above summarizes the trajectory characteristics of the Pluto/Charon encounter, and Figure 10 illustrates the encounter geometry for an 8-year flight time, 2004 JGA option. The actual encounter design will be refined in consultation with the science PI's.

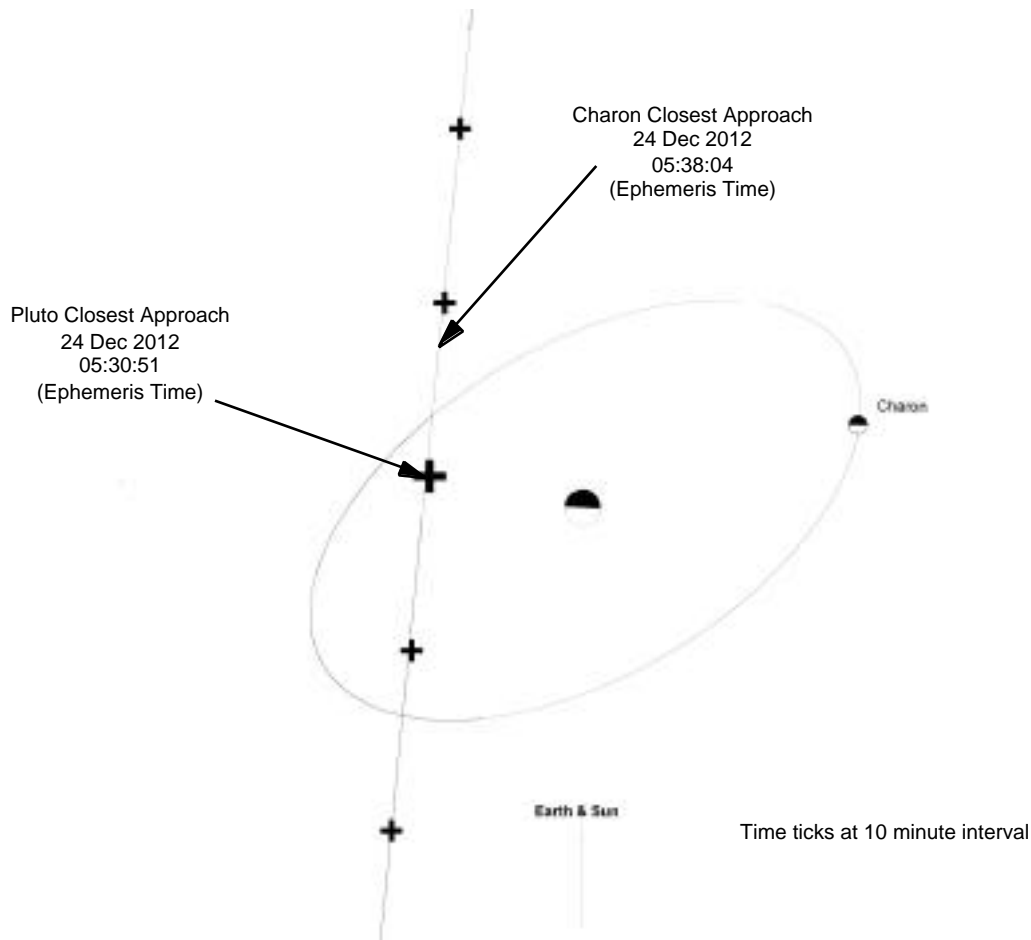


Figure 10. Pluto encounter geometry

A representative Pluto encounter animated "movie" has been made to aid the proposer in visualizing typical encounter geometries and timing. The encounter animation contains a sample view of a possible encounter. Included in the animation frame are traditional trajectory geometry data such as range to target and angle information. It is possible to freeze the playback and obtain frame-by-frame information, should you desire it. Also in the frame are appropriate text messages about key trajectory events and audio descriptions of the encounter by the creators of the animation. It is intended to help with the development of the

proposer's encounter science sequence timeline. Within limits, encounter geometries other than that shown in the movie are possible. However, the requirement for Sun and Earth occultations places rather severe limits on the encounter trajectory. A copy of the Pluto Express Encounter Animation can be obtained at the World Wide Web (WWW) site ftp://ftp.jpl.nasa.gov/pub/movies/pluto_1.mov (Caution: this file exceeds 100MB; download could be time consuming). Or, you can ftp from [ftp.jpl.nasa.gov/pub/movies/pluto_1.mov](ftp://ftp.jpl.nasa.gov/pub/movies/pluto_1.mov). This animation is playable by Quicktime on a Macintosh or PC. If needed, you can also download an appropriate version of Quicktime from Internet URL <http://www.apple.com/quicktime/download/index.html>. It is suggested that playback of the animation occur on a PowerMac for best results.

2.2.1.4 Extended Mission to the Kuiper Belt

The recent discovery of the Kuiper Belt and information about the number and distribution of bodies in it has made it desirable to determine whether the Pluto Express mission could also explore this region of the Solar System after the Pluto encounters.

The mission philosophy is that an extended mission to the Kuiper Belt is not to drive development cost or reliability requirements for the mission. Pluto/Charon Group 1 objectives alone are to drive the mission. Nothing will be done to preclude such a mission, however. If, as the Pluto encounter nears, the spacecraft appears able to perform an extended mission, funding and plans for an extension will be considered at that time.

From a feasibility standpoint, the Pluto-Kuiper Express spacecraft seems well-suited to conducting additional flybys and returning data from these encounters to Earth, at least out to distances of 45-50 AU. A mission analysis shows that with $> 4 \times 10^4$ 100-400 km ("intermediate-sized") objects and perhaps $6 - 10 \times 10^9$ comets in the Belt at distances of 50 AU or less (extrapolated from observations which currently cover a narrow portion of the sky), it is quite likely that the Pluto Express spacecraft can be retargeted for a close encounter of at least one Kuiper Belt object. For example, to reach one of the 100-km diameter-class objects detected from ground-based telescopes, statistics show that the spacecraft trajectory must be turned only about 0.5 deg, on average; this will require a 50-80 m/s ΔV maneuver after the Pluto encounter. Since the Pluto Express spacecraft is expected to carry about 90 m/s of ΔV capability at launch, it is possible that 50-70 m/s of capability will still be available after the Pluto encounter. Reaching a comet-sized object in the Kuiper Belt will be easier in the sense that the comets are $> 10^5$ times more numerous than the ground-detected objects. However, it will be more difficult to determine the orbit of such a small body beforehand. The actual selection of specific targets need not be made until well into the mission. Indeed, it may be possible for the science imager on board to detect an object sufficiently near the flight path that a trajectory correction maneuver could intercept it.

2.2.2 Spacecraft System Design

2.2.2.1 Applicable Standards

The following standards apply:

- The metric system of measurement
- X2000 Mission Data System standards for software implementation
- Reliability, Quality Control, and Safety standards will be tailored to the mission with specific emphasis as appropriate for a long, but cost-capped, mission and in accordance with the project risk management approach

2.2.2.2 System Overview

The flight system for the reference mission is envisioned to consist of a 3-axis stabilized spacecraft bus that houses the engineering and science electronic subsystems, a high-gain antenna subsystem and a propulsion module with the attached proposed Advanced Radioisotope Power Source (ARPS) and the kick stage rocket motor. The actual spacecraft power source is yet to be defined; however, the ARPS creates the most challenging radiation environment to which the science payload should be designed. A view of the spacecraft concept is shown in Figure 11. The science instruments will be fixed-mounted to the spacecraft bus; there will be no articulating pointing platform. Instrument pointing will be accomplished by changing the attitude of the entire spacecraft.

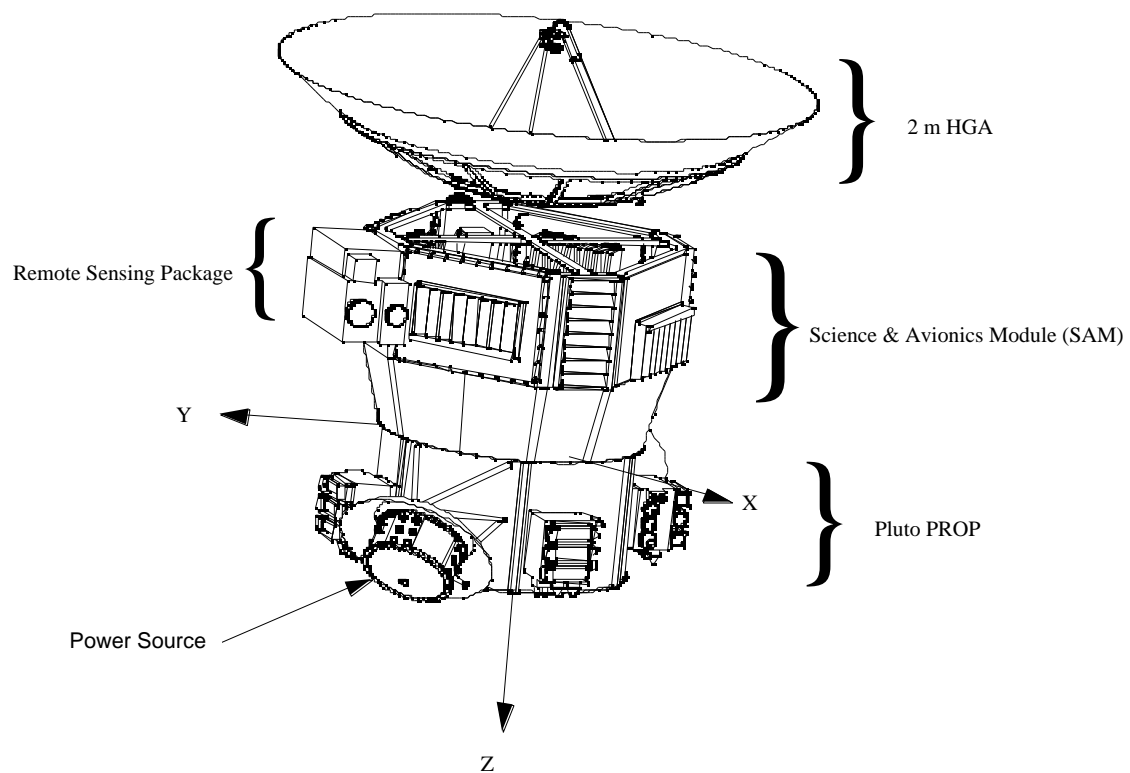


Figure 11. One possible Pluto-Kuiper Express spacecraft configuration

The major hardware elements are depicted in Figure 12.

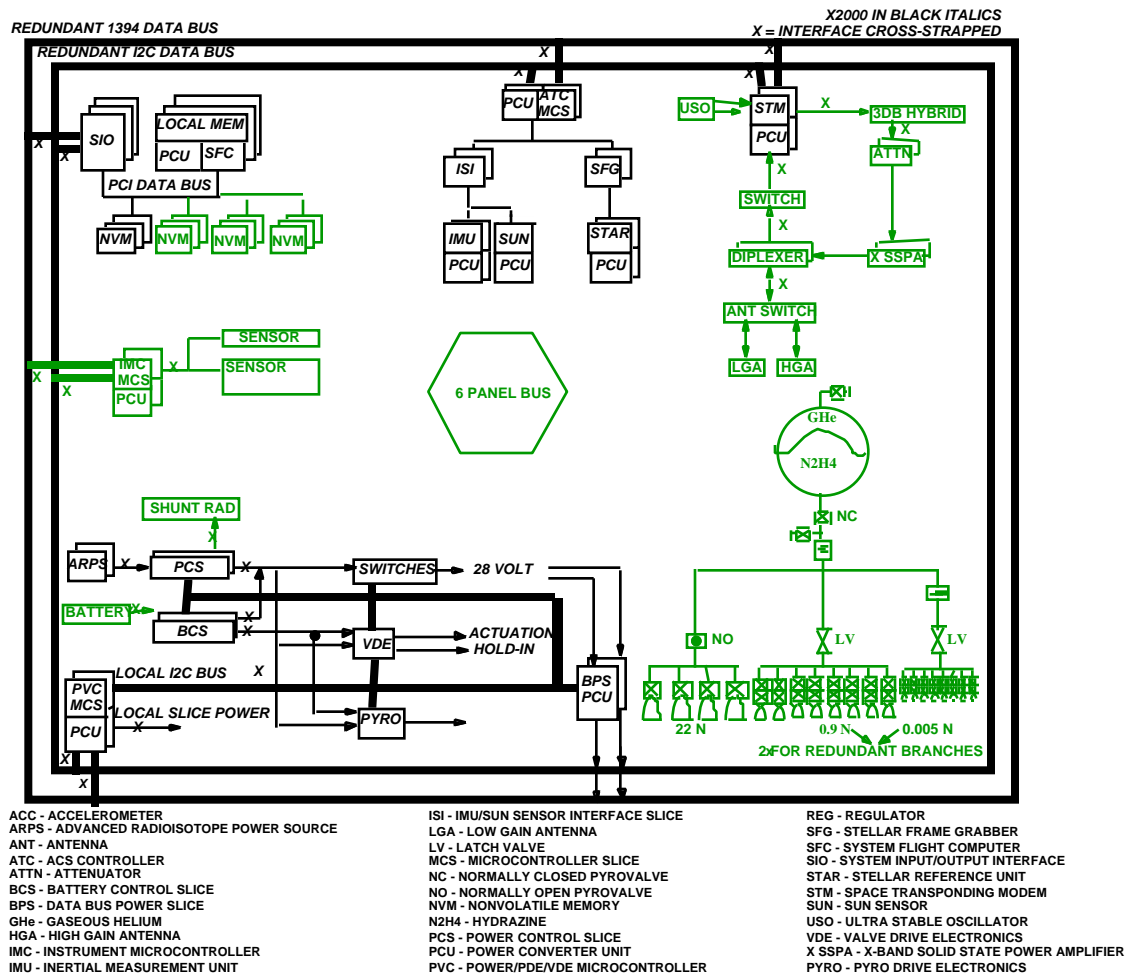


Figure 12. Pluto-Kuiper Express functional block diagram.

The current approach assumes that a substantial portion of the engineering subsystems will be designed and qualified through the JPL technology development program, X2000. The electronics design will incorporate advanced technologies to allow integration of several functions onto a single substrate. By decreasing the size of the electronics while increasing functionality, the electronics mass will be significantly decreased for the Pluto-Kuiper Express mission as compared to previous missions. The integration of the electronics into a small volume will also reduce the mass of the cabling required to integrate these functions. Additionally, the majority of the electronics developed by X2000 will be radiation hardened to 1 Mrad, and, therefore, very little, if any, additional shielding mass will be required to meet the 10-krad requirement for Pluto-Kuiper Express.

Since X2000 is just getting started and has a very aggressive program, some of their deliverable products may not have the performance envisioned today. Whenever possible, this has been foreseen in this AO by the science allocations identified. As X2000 matures and the final flight performance and components are determined, the flight system and instruments will need to review and finalize the functions and capabilities to be flown. The approach assumed for the integration of the science payload into the engineering system is to minimize the duplication of function and, thereby, allow maximum science return for the minimum mass and power. To achieve this, an integrated team will need to determine the distribution of functions between the science payload and the engineering system. Concurrent engineering and teamwork will be required to ensure that the science objectives are met within the resource constraints of the mission.

2.2.2.3 Mass

The mass of the total science payload shall be less than the allocations in Table 4 (Sec. 3.A) including any radiation shielding and reserves.

2.2.2.4 Power

The power allocated for science is given in Table 4 (Sec. 3.A). This allocation is a maximum for any given point in time during the mission except for possible short-term contamination prevention. The cumulative power for the total science complement may exceed this number, as long as, operationally, the science observations are sequenced so that no more than the allocation is required at any one time. Due to increased power demand during spacecraft communication periods, an additional science constraint for nonscience periods is likely as well. This constraint is not defined yet but will be less than the 7-watt operational constraint. Power transients of up to 100 W for 50 msec are acceptable.

The Power Subsystem has not yet been determined for this mission. For purposes of a common reference and because the instrument environments would be the most challenging technically, a radioisotope power source is considered here. The power subsystem provides approximately 130W of electrical power at Pluto encounter.

The Power Subsystem would regulate and convert the output voltage of the ARPS such that loads receive regulated 28 ± 2 VDC. Any high-voltage requirements will be the responsibility of the science investigation. Telemetry will be available on all switched power lines.

2.2.2.5 Volume

The volume allocated to the Pluto science instruments is broken into two sets: externally mounted optical instruments and internal bus instruments (USO, optical instrument electronics not housed with optics, etc).

The volume allocated to the externally mounted optical instrument package(s) is 225 mm x 400 mm x 350 mm, where the mounting interface is 225 mm x 400 mm. The aperture plane can be located on either the 400 mm x 350 mm plane, which is perpendicular to the mounting plane, or on the 225 mm x 400 mm plane parallel to the mounting plane. Radiators can also be located on either of these planes, although the best field of view to space will be on the plane parallel to the mounting plane (See Figure 13).

The volume allocated to the internal bus instruments is a 200 mm x 400 mm x 120 mm.

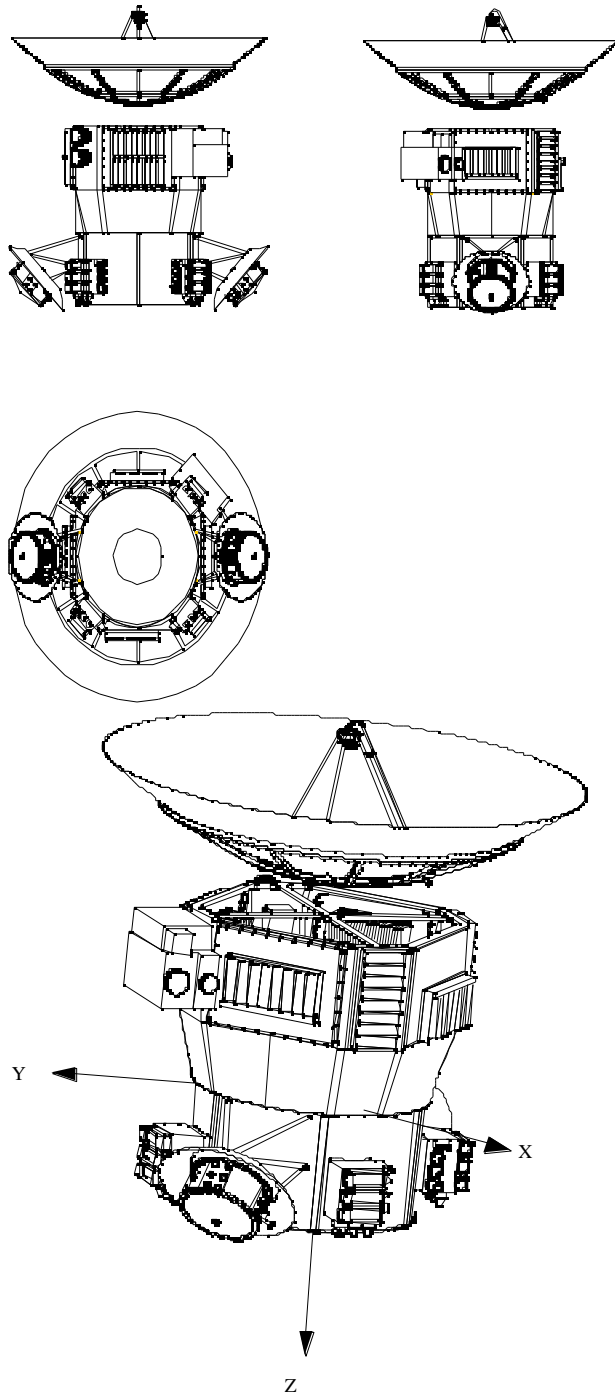


Figure 13. Pluto spacecraft and coordinate system

2.2.2.6 Thermal

All instrument hardware located internally to the bus shall be capable of an allowable flight operating and nonoperating temperature range of -20°C to +50°C.

For the externally mounted optical instrument(s), the panel interface temperature range is -20°C to +50°C. All thermal dissipation within the external optical instrument package(s) must be dissipated to space from the instrument housing(s) or radiators. Low-temperature radiators for the optical sensors are probably best located on the plane parallel to the mounting plane (if the apertures are also in this plane, the thermal impact of viewing Pluto/Charon is probably negligible but should be compared with the poorer FOV to space on another side). Radiators in any plane are not guaranteed a 100% hemispherical field of view to space (see Section 2.2.2.h).

Any science radiators or instrument temperature-control electrical heaters or coolers necessary for conducting the science investigation are the responsibility of the science investigation. The Project will supply only temperature sensors and heater switches related to maintaining the instruments within flight allowable temperatures or providing decontamination.

In addition to electrical power, the ARPS thermal dissipation could be utilized to heat the propulsion subsystem (see Section 2.2.2.1 below). In addition to this waste heat, the spacecraft may utilize Radioisotope Heater Units (RHU's), electrical heaters, louvers, radiators, and thermal blankets for temperature control throughout the spacecraft, including the bus.

The spacecraft thermal design will be capable of maintaining the propulsion subsystem within a 5°C and 50°C temperature range and the bus within a -20°C and 50°C temperature range throughout the mission. The current direct mission trajectory encompasses a solar range of 1 to 30+ AU.

2.2.2.7 Command, Control, and Data

The spacecraft data subsystem is being developed by the X2000 program and is centered around 2 system flight computers (SFC) shared between engineering and science tasks such as data processing, editing, compression, etc.

The SFC will control one redundant high-speed and one redundant low-speed data bus. The protocol standard for the high-speed bus is IEEE 1394. The protocol standard for the low-speed data bus is I²C. The I²C bus is used for configuration purposes and science instrument commanding.

A generic microcontroller will serve as the standard interface between the data buses and remote terminals such as instruments. Each microcontroller will provide interfaces to the four data buses: prime high-speed, backup high-speed, prime low-speed, backup low-speed. Two microcontrollers will be supplied by the spacecraft for use by the remote sensing instrument package. Their characteristics are defined below and in the "Description Of X2000 Components Available For Use In Instrument Proposals" document of the Outer Planets Program Library, available over the Internet through URL <http://outerplanets.LaRC.NASA.gov/outerplanets>. The radio science instrumentation is expected to use the microcontroller assigned to the Small Deep Space Transponder (SDST) as its bus interface. The mass, power, and cost for these microcontrollers need not be covered within the payload resource allocations of Table 4 in Section 3.1. Any science data processing software that runs on the microcontrollers or the SFC must be supplied and budgeted by the science investigation, however.

The spacecraft data system will include bulk data storage. The current baseline design employs nonvolatile flash memory (NVM). Due to the low downlink rate from Pluto and the rapidity of transit of the Pluto-Charon system, essentially all of the data near closest encounter will be recorded. Consequently, the bulk data storage will be sized to redundantly store all acquired science data plus storage overhead up to 6 Gbits of total memory for the approximate period between E-8 hr to E+4hr.

The planned software operating system for the spacecraft is VxWorks. The planned programming language is C++.

The spacecraft will provide time distribution across the command bus with an accuracy to-be-determined (expected value = 30) msec relative to the spacecraft clock. The instruments can use this to time tag their data when its packet is sent to the spacecraft data system. Otherwise, the spacecraft will time tag the payload packets when received by the data system within to-be-determined (expected value = 30) msec. Each downlink frame is time-tagged to 30 msec relative to the spacecraft clock at the time the frame is put together by the data system.

Tentative key requirements for the total data subsystem are:

System processor speed	30 MIPS
High-rate bus bandwidth	100 Mb/s
Low-rate bus bandwidth	100 kb/s
Data storage	up to 6 Gbits

Microcontroller characteristics:

speed	10 MIPS
8-bit parallel ports	4
UART ports	2
UART speed	1.5 Mb/s
PCI bus interfaces	1
I ² C subnet	2

Only a fraction of the data system capabilities defined above will be available to support science tasks as reflected in the resource allocations of Table 4 in Section 3.1.

2.2.2.8 Fields of View

The stray-light field of view (FOV) for the optical instrument boresights is a minimum of 30° half angle from nominal. Hardware at the edge of the 30° stray light FOV includes the HGA, thermal blankets, and possibly louver assemblies for apertures in a plane perpendicular to the mounting plane. Since materials for these items are still to be determined, worst-case surface optical properties are to be assumed. This worst-case corresponds to apertures in a plane perpendicular to the mounting plane. For apertures in the plane parallel to the mounting plane, the FOV will be greater.

For optical instrument radiators, the FOV at the mounting plane is a minimum of 30° in any direction. As a radiator surface moves away from the mounting plane, the FOV angle increases. At approximately 350 mm from the mounting surface, the FOV in the current configuration is approximately 60° to 70° in the worst case directions (namely the HGA above and propulsion system blankets below). The surfaces that the radiators will see under operating conditions at Pluto are the HGA, thermal blankets, and potentially louver assemblies, if mounted perpendicular to the mounting plane. Although the surface temperatures of these items are extremely cold at Pluto, any cryogenic (100 K or less) radiators will be impacted and should be shielded/sized accordingly. Radiators in the 180 K range will have only minor impacts. Since materials for these items are still to be determined, worst-case thermo-optical properties are to be assumed.

2.2.2.9 Coordinate System and Mechanical Design

The flight system configuration, shown in Figure 13, consists of the High Gain Antenna (HGA) assembly, the Science and Avionics Module (SAM), and the propulsion subsystem (PROP). The HGA assembly insulates a 2-m reflector, the feed and secondary structure, and may provide the sun sensor mounting interface. The antenna will most likely consist of

a composite structure. As the telecom system is further defined, the size of the antenna may be modified.

The spacecraft coordinate system is as shown in Figure 11. The spacecraft Z axis is located through the centerline of the spacecraft with +Z in the direction the engine nozzle is pointed. The X-Y plane intersects the Z axis at the interface between the bus/upper shell structure and the propulsion system and oriented with +X in the direction of the instrument boresights.

Below the HGA assembly is the SAM, see Figure 11. The SAM houses all of the science equipment and all of the spacecraft avionics. The four large flat sides of the SAM are referred to as the bus shear plates. These shear plates are where most of the internal bus hardware will be located. The four smaller sides of the SAM are referred to as the frame panels and provide the frame for mounting the shear plates. External bus hardware is ideally mounted on the frame panels, while internal bus hardware can be mounted to the frame panels as needed. The adapter structure seen below the bus provides the transition from the 8-sided bus to the circular interface of the propulsion system. The adapter also provides additional mounting surface for hardware mounted outside the bus. This entire assembly (shear plates, frame panel, and adapter) comprises the Science and Avionics Module (SAM) structure. The shear plates are anticipated to be made of aluminum. The frame panels and adapter may be made of either aluminum, honeycomb, or composite. The optical package is anticipated to be mounted to a frame panel. Figure 14 shows the apertures on the plane perpendicular to the mounting interface. Although this currently appears to be the most favorable direction for the current spacecraft configuration, this direction is not required. Please note that radiators are not depicted in the optical package cartoon shown in Figure 14. Any electronics for the optical package that are mounted internally to the bus would be located on a shear plate adjacent to the optical package.

Below the bus is the propulsion subsystem. The system depicted in Figure 11 is only a strawman concept and is subject to significant change once a propulsion system contractor is chosen. The current strawman propulsion subsystem is a monopropellant system. The single tank is structurally mounted to a cylindrical core structure. This core structure also supports all of the propulsion components and the Advanced Radioisotope Power Source (ARPS).

The flight spacecraft may utilize a linear pyro separation assembly or separation nuts between the base of the propulsion subsystem and the launch vehicle adapter. The main spacecraft load path flows from the SAM structure, through the core propulsion structure and linear separation assembly (or separation nuts), to the launch vehicle adapter.

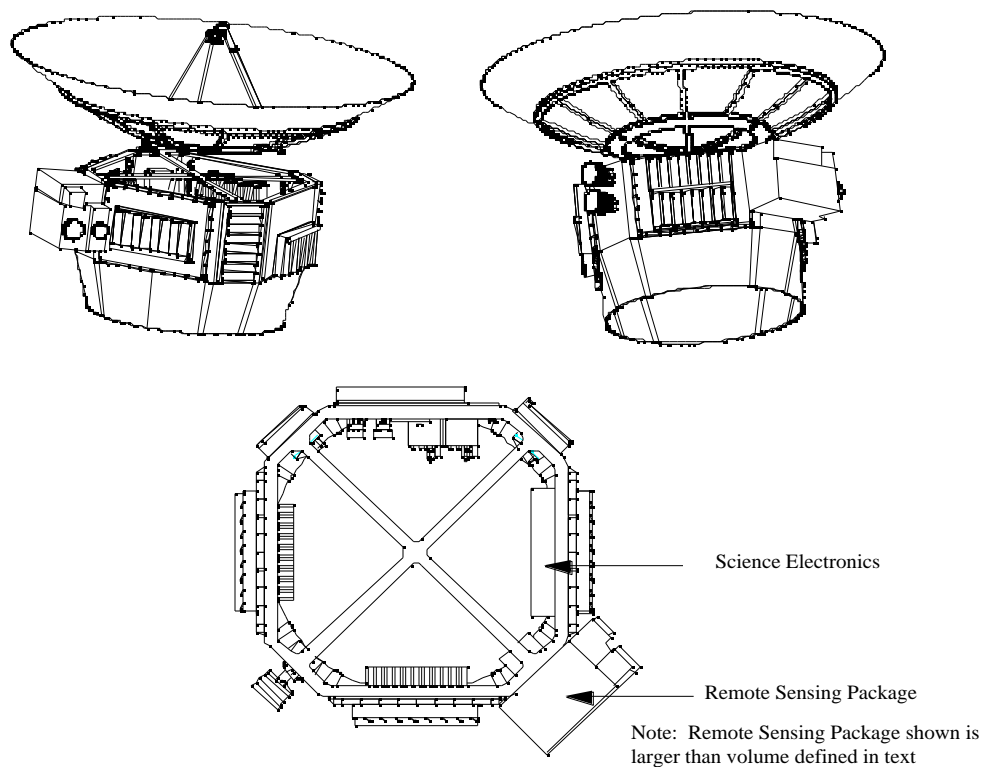


Figure 14. One possible scheme for mounting the optical science package

2.2.2.10 Attitude Control

Attitude determination will be done using star trackers, gyros, and sun sensors. Each of these sensors will be block redundant. Gyros will be part of a package that includes an accelerometer to measure spacecraft delta-V in a single axis. Attitude control will be accomplished by milli-newton sized thrusters. Delta-V maneuvers will be accomplished by firing the larger thrusters of the propulsion system.

Additional functions of the spacecraft attitude control subsystem are to navigate and control the injection kick motor. Roll control during injection must be provided by the spacecraft.

Fine pointing will be accomplished using the star tracker for attitude knowledge. Nearly continuous attitude estimation is planned. The star tracker is required to provide full 3-axis attitude determination.

The gyros will be used principally for maneuvers. The sun sensor will be used principally for attitude acquisition during cruise and faults. The sun sensor may not be sensitive enough to be used for the entire cruise to Pluto.

Key baseline requirements for the overall attitude control system are

pointing accuracy	7 mrad
pointing knowledge	3 mrad
pointing stability	1 mrad in 1 sec
	20 μ rad in 10 msec
maximum slew rate	2.6 mrad/sec
maximum slew acceleration	0 μ rad/s ²

Remote sensing payload proposers should, as part of developing their integrated coordinated near-encounter observing sequence, assess the acceptability of the available spacecraft slew rates and accelerations. If these are judged to be unacceptably slow, the proposed payload should include a supplemental pointing system that better meets the science objectives. Note, however, that the resources (mass, cost, power, etc.) for such a pointing system must be covered within the allocations of Table 4 in Section 3.1.

2.2.2.11 Telecommunications

The Telecom Subsystem for the Pluto-Kuiper Express reference mission consists of a 2-meter high-gain antenna, block redundant 20-Watt RF X-band Solid State Power Amplifiers (SSPA's), and block redundant Small Deep Space Transponders (SDST's). Due to the power limitations, the RF output of the SSPA may need to be reduced to fit within the power system capabilities. A top-level diagram showing the telecom system architecture is shown in Figure 15.

The telecommunications configuration shown is a unified uplink/downlink X-band design such that all telecom link functions can be utilized simultaneously.

- Command
- Telemetry
- Doppler Tracking
- Ranging

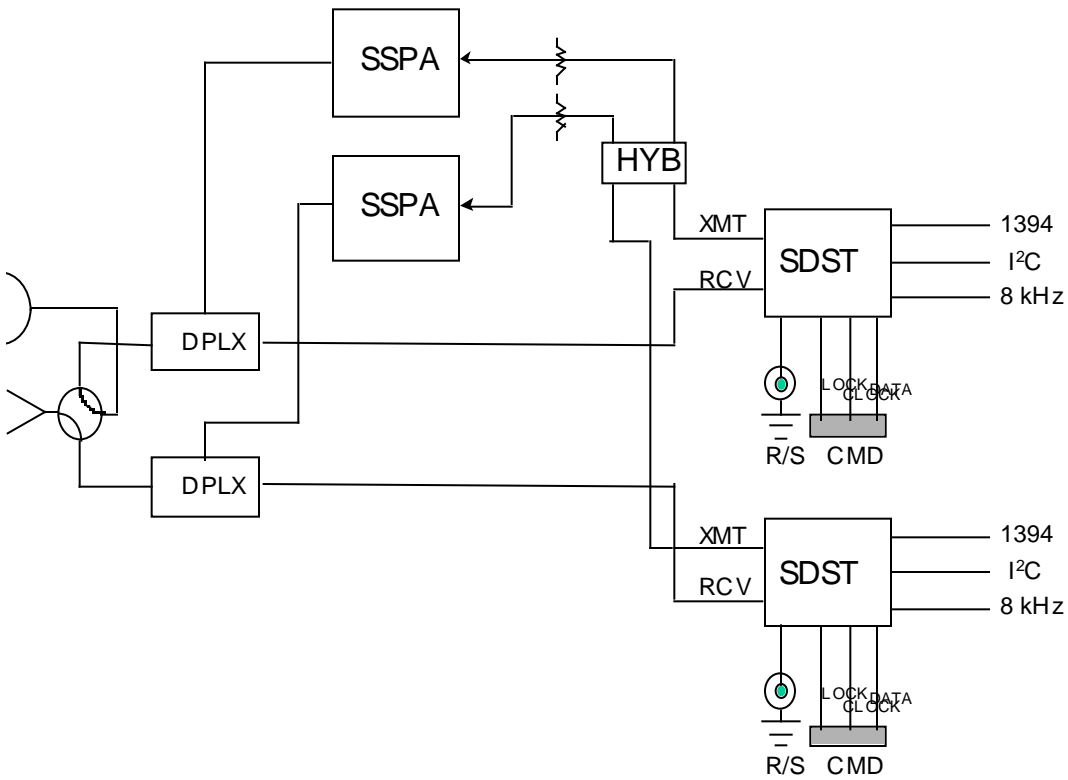


Figure 15. Pluto-Kuiper Express telecom system architecture

Table 2. Pluto-Kuiper Express telecommunications parameters

<i>Parameter</i>	<i>Pluto-Kuiper</i>	<i>Units</i>
Transmitter Power	5 - 20	Watts
High Gain Antenna	40	dBi-RCP
Low Gain Antenna	6	dBi-RCP
Science Uplink Command Rate	2	bps
Typical DSN Lockup Time	7	min
Data Rate @ 40 AU	267	bps

Downlink rate assumes 70-m DSN antenna at 20° elevation angle and 90% weather. Uplink command rate assumes 70-m DSN transmitting at 20 kW to the HGA and represents the effective transmission rate for science commands (the actual bit rate sent to the spacecraft is substantially higher).

Since both the DSN and flight system have constant power transmitters, the division of power between simultaneous links will vary depending on specific link configurations. This will affect link performance when supporting multiple links at once. Key communications parameters for the Pluto-Kuiper Express mission at 40 AU are listed in Table 2.

2.2.2.12 Propulsion

The propulsion subsystem will provide the required onboard incremental changes in velocity and reaction attitude control capability for the spacecraft over the lifetime of the mission. The total propulsive delta-V requirement is baselined at 90 m/s. This is sized for the Jupiter gravity assist trajectory reference mission. A monopropellant hydrazine system is utilized. For delta-V maneuvers, large spacecraft turns, and nominal attitude control, 22-N and/or 0.9-N thrusters are used. For attitude control and pointing during science sequences, 5-mN thrusters are used.

2.2.3 Launch Vehicle

2.2.3.1 Launch Site

The expected launch site will be either the NASA Kennedy Space Center or the U.S. Air Force Cape Canaveral Station, Florida, USA.

2.2.3.2 Launch Vehicle

The final launch vehicle selection has not yet been made. The reference mission assumes that the Pluto-Kuiper Express spacecraft will be designed for launch on either the STS/IUS/Star 48V or a Delta 3 (or Atlas 3)/Star 48V launch systems. A final decision on the launch system will be made in late 2000 or before. In either case, Pluto will utilize a JGA trajectory. The reference mission in this AO has a nominal flight time of 8 years to Pluto. The actual flight time is expected to be 8-10 years depending on launch conditions, spacecraft mass, and final selection of Jupiter flyby distance.

2.2.4. Environmental Requirements

Figure 16 shows the best estimate of the integral dust particle fluence on the Pluto spacecraft over the entire mission.

Table 3 gives the expected fluence of particles with masses and velocities great enough to penetrate 100 mils of aluminum assuming a particle density of 2.5 gm/cm^3 . Fluences are

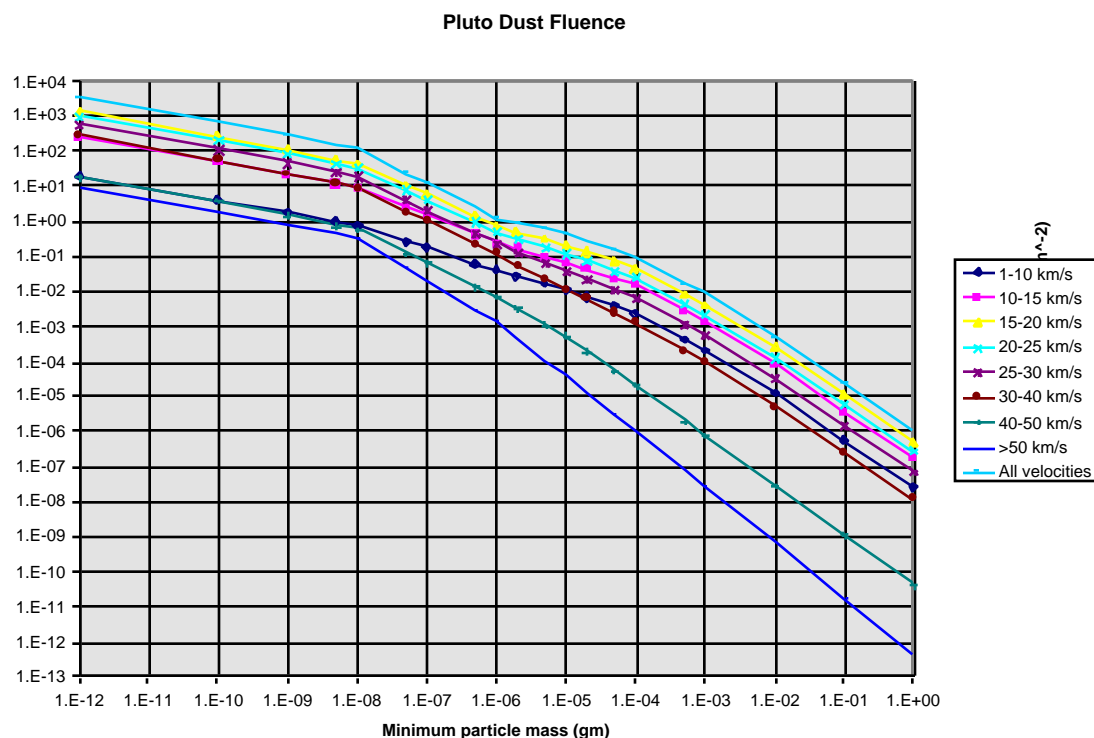


Figure 16. Integral Pluto dust particle fluence

shown for surfaces having random orientation in space, orientated normal to the spacecraft velocity vector (+v), and oriented normal to the spacecraft negative velocity vector (-v). Over 75% of the total fluence is accumulated in the first year after launch primarily on surfaces facing the spacecraft velocity direction, which is roughly in the +Z direction during early cruise. Proposers will need to consider whether or not they need to provide protection for their instruments against such micro-meteoroid impacts.

Table 3. Fluence (number/m²) of 2.5-gm/cm³ particles on the Pluto spacecraft that will penetrate 100 mils of aluminum

Time period	Surface orientation		
	random	+v	-v
Entire mission	0.15	0.40	3.6 x 10 ⁻⁷

Other environmental requirements are defined in the "Environmental Requirements" document of the Outer Planets Program Library, available over the Internet through URL <http://outerplanets.LaRC.NASA.gov/outerplanets>.

2.3 Mission Development Concept

2.3.1 Flight System Design and Deliveries

Though the three OP/SP spacecraft will be launched over a period of 3-4 years, the initial spacecraft design will be performed by the same personnel assigned to a joint design team. This team will continue into the detailed design of the Europa Orbiter and Pluto-Kuiper Express spacecraft while identifying areas of commonality for incorporation later into the detailed design of the Solar Probe spacecraft. Common subsystem designs will be used wherever possible to minimize the cost of developing and testing each spacecraft.

The OP/SP Project expects to employ the JPL Mission Data System (MDS) as its end-to-end data system. The MDS is currently under development and comprises both flight and ground software used by multimission and project personnel to operate the spacecraft. MDS will be used in software development, system test, and in actual mission operations and will enable the missions to collect, transport, store, and act on both commands and telemetry. The MDS software architecture employs an object-oriented approach. The MDS spacecraft component will provide a standard interface to the science instruments including time synchronization, commands, data acquisition, memory loading, and memory readout functions. The software architecture is designed such that a core set of software functions are coded and used for all missions. Some mission-specific software will be required to specifically address those unique aspects of each mission, spacecraft, and payload. This core architecture will allow for software reuse, reduced cost in the development and testing of the software, smaller flight operations, faster sequence turn-around times, and improved science return in the event of required failure recovery responses.

Science proposers who intend to exploit available spacecraft computer resources will need to be compatible with the MDS software architecture and design, at least for software that is resident in the Spacecraft Flight Computer (SFC). The extent to which any instrument flight software that runs on an internal instrument computer or any investigator-generated ground sequence planning, Ground Support Equipment, or data analysis software will need to adhere to MDS standards will be specified in an OP/SP Software Management Plan. Instrument proposers should plan to have at least one software expert in residence at JPL for at least 6 months prior to instrument PDR for training in the MDS methodology, development environment, and tools. MDS coding will be in C++, and the operating system is VxWorks/Tornado. The required software licenses will be provided by the Project. MDS documentation will be provided including a Development Plan specifying the software development process, coding standards, review criteria, and configuration management approach; a Capabilities Catalog describing the capabilities supported by the MDS

architecture; and a Users Reference Guide. Science instrument providers will be expected to participate in developing command and telemetry dictionaries, associated system design constraints, and instrument flight rules and constraints.

The planned X2000 First Delivery includes multimission avionics, software, and other equipment for the three missions. The recurring cost for the flight equipment is expected to be comparatively low. The propulsion modules and science packages are unique, however, and they will be a significant factor in the total cost of those missions. These mission-unique costs are borne by each individual mission, but by using common flight support and test equipment and common ground and flight software modules, each mission can reduce its integration and test costs.

Whenever possible, leveraging of technology developments supported by other NASA missions and/or technology development programs will be used where the capabilities match the needs of OP/SP. Such arrangements include incorporation of technologies supported by the New Millennium and Mars Programs. Some mission-unique technology (e.g., heat shield/antenna for Solar Probe) requires that OP/SP wholly support the development.

Standard, reasonable services will be provided the instruments during integration and testing at the system integrator's facility and the launch site. These include:

- Sterile dry N₂ purge (to be connected after receipt at the system integrator). It is the Instrument's responsibility to provide this during shipment and delivery into the integrator's facility.
- Office space with telephones and modem connections
- Laboratory space with limited tool capability in the integration facility.

A Spacecraft Test Laboratory will be developed at the system integrator's facility to simulate the spacecraft and software. The instruments shall provide software simulators of sufficient fidelity as well as breadboards and instrument simulators to support this effort.

2.4 Mission Operations Concept

2.4.1 Integrated Mission Flight Operations Team

The Europa Orbiter, Pluto-Kuiper Express, and Solar Probe missions will share a single core flight team and a common mission data system. This approach is enabled by the common X2000 avionics design shared by all three spacecraft together with a large percentage of common flight software. Each mission will supplement the shared operations capability with a few mission-dedicated personnel including mission planners, instrument representatives, and science investigation teams.

The core flight operations team will be supported by a university-based operations team, which will be competitively chosen in 2001. The university team will be delegated selected routine flight operations tasks to enhance the ability to operate multiple spacecraft simultaneously, to support educational outreach, and to provide a potential source of trained new-hires during the 15 years of flight operations. A workstation-based ground data system design makes implementation of a replica Project Operations Center (POC) at a university cost effective. Science workstations that allow science team members to interact with the operations system from remote sites will be developed as part of the ground data system design.

2.4.2 Beacon Mode Cruise

Routine Deep Space Network (DSN) tracking during cruise will be limited to a single, 4-hour pass every two weeks. This limit on telemetry and radiometric data collection and spacecraft commanding during cruise is intended to keep operations team costs low and reflects the new NASA full-cost-accounting policy, whereby missions are charged for DSN tracking time. To prevent a spacecraft anomaly from going undetected by the ground for a period of up to two weeks, a daily spacecraft beacon monitor track will be performed to establish that the spacecraft is on Earth-point and that no onboard event has been detected that requires ground interaction until the next regularly scheduled telemetry pass. The beacon signal generated by the spacecraft is a subcarrier tone that can be received by a small (5 or 10 meter) ground antenna and detected by a low-cost receiver / detector. The daily beacon monitor check for each spacecraft may be a task delegated to the university operations team.

On-board software that supports Beacon Mode operations includes fault detection and containment software that allows the spacecraft to safe itself during cruise for up to 2 weeks without ground action. Advanced engineering data summarization, onboard alarm limit checking, onboard performance trending, and adaptive anomaly data capture capabilities will also be provided.

The assumption is that science instruments are powered off during cruise except as required for instrument survival. Approximately once a year, or as negotiated with the Principal Investigators, the instruments will be turned on, calibrated, and tested, along with encounter sequence macros that have been developed during the year. Extra DSN tracking during this week will be provided to support the additional commanding and telemetry data collection required. This annual instrument turn-on week will probably be scheduled to occur during planned science team meetings.

OP/SP data management and data transport protocols will be X2000 MDS-based and will exploit multimission TMOD data services that will have been upgraded to support the

MDS design. The MDS design assumes a common flight/ground file-based data management framework. Files will be used to package and store logical data units (objects) that may not map well into the packet model. The goal is to have management of both onboard data files and ground data files appear similar to the user. File management will support long-popular storage/access capabilities for numerous types of nontelemetry data products. File-based transport protocols will be provided for both S/C-to-ground and ground-to-ground nodes. Packetization will be provided as the underlying mechanism of flight-to-ground file data transport. The goal is to make packetization invisible to file-based data management and transport. An implication of this approach is that needed time tags and other ancillary data provided in packet headers and ancillary data packets in the traditional packet-based, data-stream-based systems will have to be provided within the data objects/data files.

2.4.3 Encounter Operations

Transition from cruise operations to encounter operations for the Pluto mission starts at closest approach - 1 year. Starting at this time, DSN coverage will increase, along with operations team staffing to support higher activity levels and mission critical events. If available within mission constraints, operations resources will be available to support instrument calibration and serendipitous science observations during the Jupiter gravity assist flyby.

2.5 Project Schedule

The Project schedule is shown in Figure 17.

3. Science Investigations

3.1 Resources for the Science Investigations

As part of the strawman spacecraft design, an allocation of resources was made for the science payload. It is expected that this payload would be developed as a fully integrated component of the spacecraft and not as a more traditional add-on subsystem. But, to set a benchmark to which design alternatives may be compared, mass and power estimates for the strawman science payload are 7 kilograms and 7 watts of power, including the PI-provided radio science ultra-stable oscillator and signal processing unit. Roughly one kilogram and one watt of these resources are allocated for radio science. The power allocations include power required for internal instrument heaters for thermal control. Decontamination heaters may exceed these power allocations, but, if so, their use will be limited by power availability. Additional details on spacecraft capabilities supporting the science investigations are given in Section 2.2.2.

Outer Planets/Solar Probe Project Preliminary Schedule (revised 98/11/12)

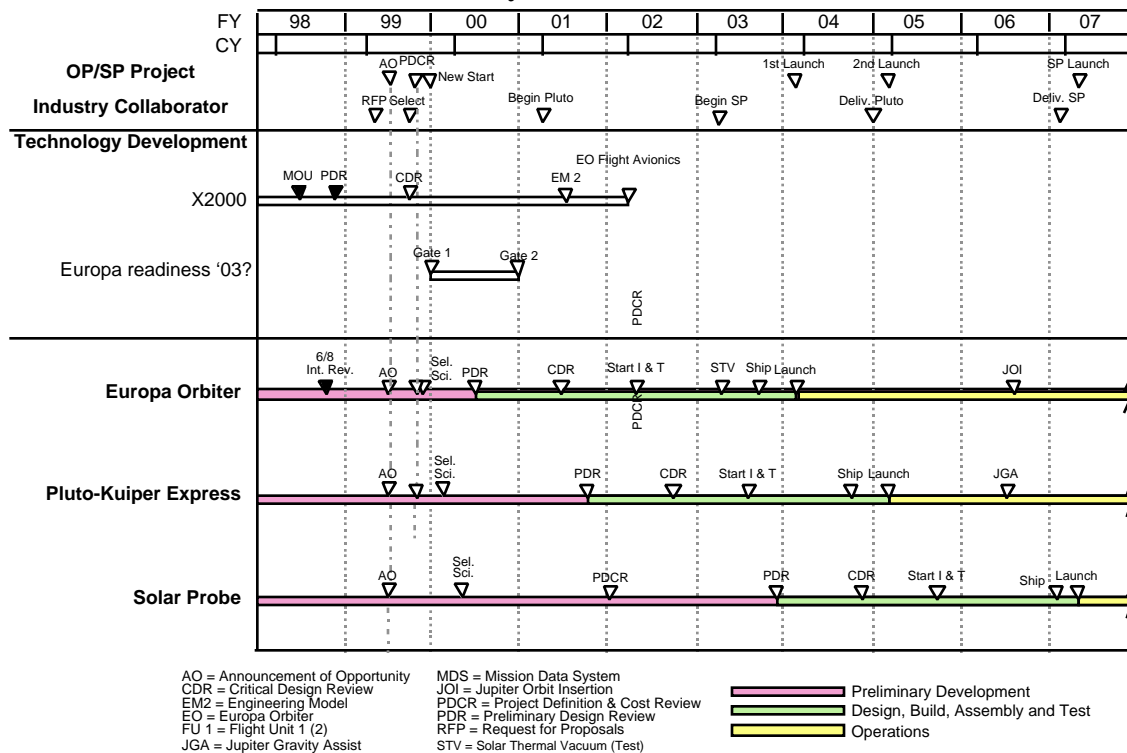


Figure 17. Outer Planets/Solar Probe preliminary schedule

Table 4 summarizes the resource allocations for the Pluto science payload. The resource allocations are listed in order of criticality. Cost and power are far more critical than others. Proposals that fall outside the allocations for the resources of higher criticality will have a lower probability of selection. Proposals that exceed lower criticality resource allocations will not be penalized provided that they also undersubscribe some higher criticality resource.

Investigations may exceed the allocated levels of data storage and computer processing MIPS by including the required extra memory or computer as part of their own hardware deliverable. X2000 parts are available for use by science investigators for this purpose, as listed in the "Description Of X2000 Components Available For Use In Instrument Proposals" document of the Outer Planets Program Library, available over the Internet through URL <http://outerplanets.LaRC.NASA.gov/outerplanets>. The cost and mass to cover use of such parts must be included in the instrument totals.

Table 4. Pluto science instrument resource allocations in order of criticality

<u>Resource</u>	<u>Criticality</u>	<u>Units</u>	<u>Allocations</u>	
			<u>Remote Sensing</u>	<u>Radio Science</u>
Cost	Higher	M\$ (real yr)	20	5
Power (average)	Higher	watts	7.5	N/A
Mass	Lower	kg	6	1
Data storage	Lower	Gbits	2.2	0.01
Computer processing	Lower	MIPS	23	2
Downlink data rate	Lower	bps	150	2
Bus bandwidth (asynchronous)	Lower	Mbps	25	1
Volume (internal)	Lower	cm	22x35x40	0
Volume (external)	Lower	cm	1320cm ² x12	440 cm ² x12

Any instrument purge equipment beyond fittings and internal plumbing that are part of the instrument will not have its mass charged against the above instrument allocations. Any instrument covers must be included in these allocations even if they are jettisoned.

It is anticipated that the teams of remote sensing and six radio science investigators selected via this AO will be kept small for reasons of efficiency and economy. The total funding available in real year dollars to support these investigators (over and above the instrument development costs allocated in Table 4) is as follows:

<u>Team</u>	<u>Development phase</u>	<u>Operations phase</u>
Remote sensing	\$2.4M	\$9.2M
Radio science	\$1.2M	\$4.3M

Table 5 gives the anticipated profile of available funds by fiscal year for each investigation (hardware plus science investigators). Proposals should not plan to exceed these yearly funding levels by more than 20% in any given year unless funding below the indicated level is carried forward from an earlier fiscal year. In no case shall the total funding for the investigation exceed the allocated total.

3.2 Interaction with the Project

3.2.1 Project Fiscal Policy

The sections below include items that are pertinent for consideration by proposers in preparation of responses to this AO.

Table 5. Investigation (instrument and investigators) new obligation authority funding profile guideline in millions of real year dollars for the development and operations phases

Development Phase

	FY	<u>00</u>	<u>01</u>	<u>02</u>	<u>03</u>	<u>04</u>	<u>05</u>	<u>Sum</u>
Remote Sensing		4.3	5.6	6.5	4.5	1.4	0.1	22.4
Radio Science		0.9	1.3	1.8	1.7	0.4	0.1	6.2

Operations Phase

	FY	<u>05</u>	<u>06</u>	<u>07</u>	<u>08</u>	<u>09</u>	<u>10</u>	<u>11</u>	<u>12</u>	<u>13</u>	<u>14</u>	<u>Sum</u>
Remote Sensing Team		0.4	1.1	0.3	0.3	0.3	0.3	0.3	1.5	2.8	2.1	9.2
Radio Science Team		0.2	0.3	0.1	0.1	0.1	0.1	0.2	0.8	1.4	1.0	4.3

3.2.1.1 Budgetary Authority

NASA will annually allocate New Obligation Authority (NOA) to JPL for the Outer Planets/Solar Probe Project based on an Implementation Plan and updates submitted by the Project. In turn, the Project Office will allocate NOA annually to the Project Work Breakdown Structure primary elements based on the NASA NOA, the plans submitted by the leaders of each element (two of whom are the Chief Scientist and the Flight Instrument Development Manager), and the needs of the Project. Each mission (Europa, Pluto, and Solar Probe) has a Project Scientist, and one of them has additional duty as Chief Scientist. The Science Investigation Principal Investigators whom NASA selects through this AO will negotiate their Statements of Work (SOW's), budget submissions, and authority with the Flight Instruments Development Manager, who will be assisted in these negotiations by the appropriate Project Scientist. The resulting SOW and funding schedule will be documented in a contract between JPL and the PI's institution; this contract will be modified, if necessary, through the course of mission development and operations, covering the period of time from contract award to final delivery of science products after the end of the mission.

3.2.1.2 Cost-Capped Mission Budget Environment

Proposers must understand that NASA and JPL budgets for all OP/SP activities are strictly cost-capped. This capped cost includes launch vehicles, integration and interfaces, launch operations, and all flight and ground systems. Mission operations phase costs, including science operations and data analysis, will be similarly capped for each mission. Total project costs will be a primary consideration in all design and development decisions and activities. Other requirements will have flexibility and will be prioritized to provide adequate margins and options for staying within cost and schedule constraints.

3.2.2. Project Organization

Overall project leadership and coordination is provided by the Project Manager and Project Office staff. The project is organized as shown in Figure 18. The Chief Scientist is a member of the Project Office staff, is appointed by the Project Manager, and reports to the Project Manager.

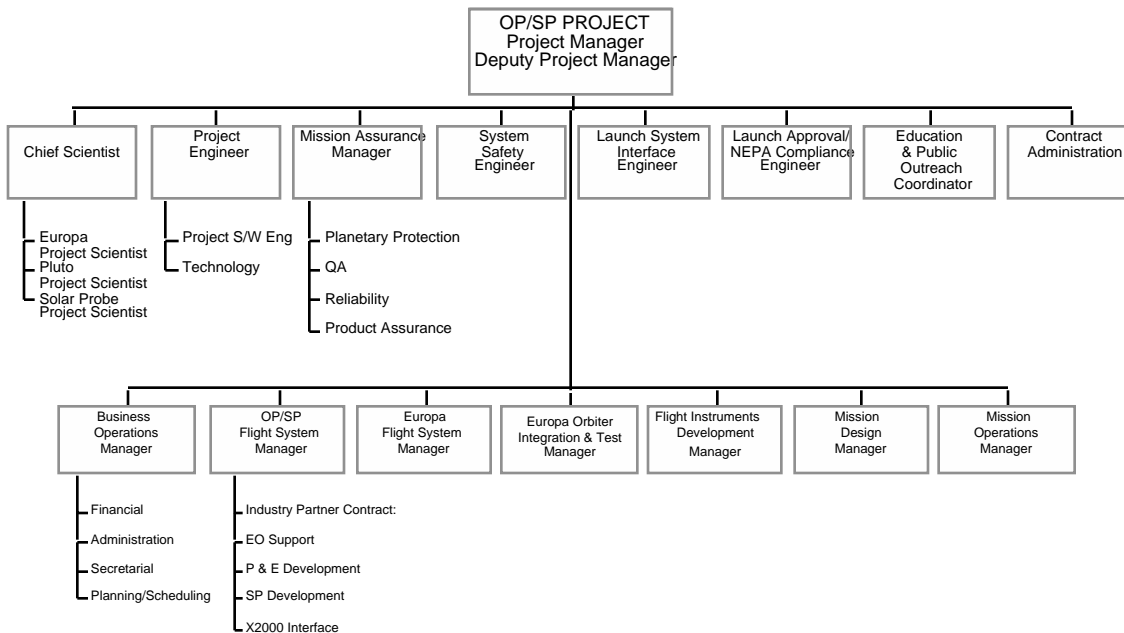


Figure 18. Organization chart for the Outer Planets/Solar Probe Project.

3.2.2.1 Science Investigators as Members of Project Teams

PI's and their lead instrument developers will become members of an integrated implementation team for their respective mission.

Primary interfaces with each mission implementation team will be in the following areas:

1. Trajectory/Navigation/Mission design.
2. Flight System (including mechanical and electronic interfaces, major system trades).
3. Software Development.
4. Mission Assurance (including electronic parts, risk management, quality assurance).
5. Assembly, Test and Launch Operations.
6. Mission Operations and End-to-End Data Flow (including flight/ground Mission Data System).

The avionics, software, and mission data system for the three missions (and other "customer" missions) will be developed in common by the X2000 First Delivery Project, based at JPL, and their numerous partners and contractors in industry, academia, and Government. Some of the electronic parts developed by X2000 will be available for use in science instruments, such as microcontrollers, memory, and power converters (see the "Description Of X2000 Components Available For Use In Instrument Proposals" document of the Outer Planets Program Library, available over the Internet through URL <http://outerplanets.LaRC.NASA.gov/outerplanets>). Each item is intended to be made available commercially and can be considered in the design of the instrument. The OP/SP Project will handle all interfaces with X2000 and will consult with PI teams as appropriate.

3.2.2.2 Relationship Between Science Teams and the Outer Planets/Solar Probe Project

The Project Scientist for Pluto will have overall responsibility for the coordination of the mission's science and the achievement of the mission science objectives through chairmanship of the Mission Science Team, the other members of which will be the Science Investigation Principal Investigators.

Principal Investigators and/or key members of their teams will need to be available for frequent on-line concurrent working sessions. In addition, co-location of key Science Investigation Team members may be required during high-activity periods.

As with the design of each mission, details of the project organization and interactions will evolve over time to meet the needs of the project and each mission.

3.2.3 Encounter Science Team Selection, Participation, and Management

The OP/SP development and operations environment will require that individuals selected to produce the science investigations work closely with JPL and other team members on producing investigation hardware, software, mission design, and the flight system which supports the investigations. It is anticipated that the instrument teams selected in response to this AO will be small and consist mainly of those who will design hardware and software for the mission. Scientists whose role would be primarily in the areas of data reduction and analysis and interpretation of the resulting information will not be funded as part of the initial team in order to save costs.

After launch and as the spacecraft near their science targets, NASA plans to select via a to-be-determined process a broader team of scientists to provide the expertise required to

successfully conduct the observations and reduce, analyze, and interpret the data. The core of the team, it is anticipated, will be those who designed the investigations during the prelaunch phase, with possible changes reflecting career moves, retirements, and the evolving knowledge base in planetary and solar science. The intent is to retain the crucial expertise needed to fulfill the science investigation, while bringing in new people who can maximize the value of the science returned from the mission.

3.2.4 Mission Assurance Requirements

OP/SP mission assurance requirements for science instruments can be found in the "Instrument Mission Assurance And Safety Requirements" document of the Outer Planets Program Library, available over the Internet through URL <http://outerplanets.LaRC.NASA.gov/outerplanets>.

3.2.5 Principal Investigator Responsibilities

Science instrument Principal Investigators (PI's) are responsible for instrument design and development, fabrication, test, calibration, and delivery of flight hardware, software, and associated support equipment, within project schedule and payload resources. The PI's are responsible for planning and operational support of instrument operation, data analysis, and overall conduct of each of their investigations.

A PI-funded instrument engineer for each instrument will represent the payload at the spacecraft integrator's site as a participant in the integrated development teams and to negotiate interfaces.

The specific responsibilities of the instrument PI include, but are not limited to, the following:

1. Developing an internal management plan and an experiment implementation plan.
2. Ensuring that the design, fabrication, development, and testing of the investigation flight elements are appropriate to the objectives of the investigation and assure qualification to the environmental and interface constraints.
3. Managing hardware and software margin to ensure successful integration and implementation of the experiment.
4. Hardware and software quality assurance and reliability and selection of parts and materials.
5. Ensuring that instrument hardware and software development meets the approved schedules and cost plans.
6. Establishing requirements, Interface Control Documents (ICD's), schedules, and transfer of funds through negotiation with the Project.

7. Ensuring the flight hardware is flight qualified and properly calibrated.
8. Participating in Project Science Group (PSG) meetings and associated working groups. PSG meetings will be held in conjunction with PI Working Group meetings every 6 months.
9. Conducting payload reviews.
10. Participating in Software Working Group (SWG) meetings, as required by the proposed science use of spacecraft computational resources and services to resolve requirements, process issues, and interface issues and to resolve resource allocations and operational timelines.
11. Supporting payload integration and system test procedure development and maintenance and payload hardware and software integration.
12. Participating in flight system tests and integrated end-to-end ground system tests and operation of any payload-unique Ground Support Equipment (GSE) in these tests.
13. Supporting definition of mission database contents, including, but not limited to, flight rules and constraints, sequences, payload telemetry, and commands.
14. Supporting integrated mission data/sequence development and flight software integration.
15. Supporting launch site operations planning, including safety, and launch site system tests at Kennedy Space Center/Cape Canaveral Air Force Station.
16. Planning and executing mission operations.
17. Ensuring that the reduction, analysis, reporting, and archiving of the results of the investigation meet with the highest scientific standards consistent with budgetary and other recognized constraints.
18. Preparing, certifying, and releasing a final data product (to PDS) within six months or less of data receipt on the ground.

3.3 Deliverables

3.3.1 General

The deliveries by the instrument Principal Investigator to the Project include, but are not limited to, the following:

1. Sign a Memorandum of Agreement with the Project that documents resource allocations.
2. Provide and maintain required documentation, including ICD's (see Section 3.5.4)
3. Support development and maintenance of ICD's.
4. Provide monthly Technical Progress Reports and monthly Financial Management Reports.
5. Deliver flight-qualified hardware to the flight system integrator with suitable shipping containers and any protective covers required.

6. Deliver either an Engineering Model, Protoflight unit, or a payload mass simulator and payload data interface simulator to the flight system integrator.
7. Provide necessary payload-unique GSE for stand-alone integration and launch operations.
8. Provide payload unit history log books including power-on time log.
9. Deliver investigation flight software to be resident in the spacecraft flight computer (see Section 3.3.3.).
10. Provide timely information to establish and maintain controlled baselines for software interfaces, shared computational resources, mission data, and mission operations timelines and sequences.
11. Archival science data products.

3.3.2 Hardware Delivery

The payload data interface/mass simulator, Engineering Model, or Protoflight unit must be delivered to the flight system integrator's site on or before 16 months before launch. The science payload flight units must be delivered on or before 13 months before launch. Payload flight units must be accompanied by all ground support equipment needed to support system test. Unit history log books shall accompany the flight hardware. Payload flight units must be fully qualified and calibrated before delivery; instruments will not be returned again to the PI.

3.3.3 Software

The OP/SP Software Management Plan will specify requirements on software documentation, testing, source materials, reviews, and metrics.

3.3.3.1 Software Documentation - Software/Computer Systems Interface Control Document (ICD)

Initial definition of operational timeline requirements and related resource demands (characterized by peak and typical parameters) will be negotiated in compliance with resource usage constraints placed on the science payload by the Project and documented in a software-specific section of the Preliminary ICD (with Initial Software Requirements) for:

1. Volatile and nonvolatile memory
2. Process activation frequency and duty cycle
3. Storage demands with storage duration's
4. I/O requirements for all classes (data bus bandwidth, command/telemetry bandwidth) including best available information on compliance with protocol standards or any unique data transfer methods.

Updated information for all items in the Preliminary ICD, with projections of final commitments for all resource demands, plus protocol compliance for all transactions using the spacecraft C&DH, including behavioral characteristics of timing where it is relevant to correct operations of the science payload/mission, is due with the Update Software Requirements ICD.

The committed baseline for all elements of the Software/Computer System Section of the ICD is the third delivery, due with the Final Software Requirements ICD.

3.3.3.2 Software Documentation - Other

Requirements, design, build, test, and evaluation information that provides insight into the software implementation should be provided as they become available, in accordance with the PI's normal development plan.

3.3.3.3 Software Test: Required Evaluation Procedures

Software test procedures are required and are subject to approval. The fidelity of the procedure and level of approval corresponds to the potential risks involved in the procedure. Generally, as the software testing is done in primarily a simulation and Engineering Development Unit (EDU) environment, the risk is minimal, requiring approval from only the cognizant personnel for the item under evaluation and Spacecraft Test Laboratory (STL) operations. Circumstances that may require further approvals include:

1. Use of flight hardware in the configuration;
2. Requirements for special interfaces, either hardware or software, that may require test setup and verification; and
3. Exclusive operations or continuous operations that produce resource conflicts not reconcilable among other parties.

3.3.3.4 Software Source Materials

The mission load (all executable spacecraft and payload flight software and data) is generated as an integrated load image, including initial/nominal values for all updatable mission data/system files. To develop the mission load, source code for compilation, materials for binding, and data/file load shall be provided in a timely fashion to support software development integration in the Spacecraft Test Laboratory, assembly and integration tests during science payload integration, and mission readiness tests at the launch site. The Final Software Baseline Delivery for launch is scheduled at the time of flight hardware delivery, prior to the start of science integration for final build and characterization of the launch configuration load image. Other postlaunch flight software updates are expected.

3.4 Payload Reviews

The payload PI(s) will be expected to attend the spacecraft Preliminary Design Review (PDR) and Critical Design Review (CDR), ground system reviews, and any informal reviews scheduled by integrated development teams with payload participation requiring the PI rather than the instrument engineer.

Each instrument PI will host a Preliminary Interface Requirements and Design Review (PIRDR) for their investigation. The PIRDR is scheduled as early as possible after the completion of the Functional Requirements Document (FRD)/Experiment Implementation Plan (EIP). Topics include: discussion of the EIP, discussion of the FRD, description of interfaces, I/F verification plan, and description of the safety plan.

Likewise, each PI will host a Final Interface Requirements and Design Review (FIRDR). The FIRDR occurs prior to the mission CDR, at the completion of the payload detailed design. Topics include: status of hardware design, fabrication, test, and calibration, software design and test plans, plans for integration, description of support equipment, finalization of interfaces, command and telemetry requirements, and discussion of environmental and system tests.

Prior to delivery of the flight instrument, each instrument PI will hold a Hardware Requirements Certification Review (HRCR) to ensure that the instrument meets all of its requirements and is ready to be shipped for integration on the spacecraft.

3.5 Documentation Requirements

The following is a list and description of the minimum formal documentation that will be required from instrument PI's:

1. Memorandum of Agreement
2. FRD/EIP/Safety (Combined)
3. GDS/MOS Requirements (Preliminary and Final)
4. ICD Major Milestones
 - Preliminary (with Initial Software Requirements)
 - Final (Start Configuration Control)
 - Update Software Requirements
 - Final Software Requirements
5. Instrument Design Description
6. Payload Handling Requirements List
7. Unit History Log Books
8. Acceptance Data Package

3.5.1 Memorandum of Agreement

A Memorandum of Agreement documents the investigation resource allocation (mass, power, volume and fiscal resources) between the project and each investigation PI. This is written immediately after payload selection and signed by the Project Manager, PI, and spacecraft flight system integrator designee for hardware investigations.

3.5.2 Functional Requirements Document (FRD) / Experiment Implementation Plan (EIP) / Safety Plan

Each instrument PI is responsible for writing a combined Functional Requirements Document and Experiment Implementation Plan for their investigation within 3 months of selection. Contents are negotiated with the project manager, but may be assumed to include:

1. Payload functional requirements,
2. Hardware development-and-test plans and schedule, including reliability and quality assurance plans,
3. Software development-and-test plans and schedule,
4. Cost plan for hardware and software development, fabrication, test, and calibration from selection through launch,
5. Margin management plan
6. Post-launch cost plan for instrument operation, data analysis, and data archiving,
7. Requirements for project support,
8. Personnel and hardware safety plans,
9. Contamination control plan
10. Calibration plans,
11. Science management and investigation plan,
12. Payload portion of range safety plan and payload safety at launch site.
13. Fracture control plan (for Space Shuttle launched payloads).

3.5.3. Ground Data System (GDS) / Mission Operations System (MOS) Requirements

Ground Data System / Mission Operations System requirements due dates are listed below. These primarily address instrument operation requirements and flight rules.

	<u>Europa</u>	<u>Pluto</u>	<u>Solar Probe</u>
Preliminary	9/00	9/01	9/04
Final	9/02	9/03	9/06

3.5.4. Interface Control Documents (ICD's)

ICD's are negotiated directly with the spacecraft engineering team in an integrated-development-team environment, with Preliminary ICD's required by the spacecraft PDR and final ICD's under configuration control by the spacecraft CDR. ICD's identify all payload interfaces, including, but not limited to, the volume envelope, mounting, center of mass, electrical and mechanical connections, end circuits, pyro devices, features requiring access or clearance, purge requirements, software requirements, testing, facility support, view angles, clearances, etc.

3.5.5 Instrument Design Description Document (IDDD)

The final design of the payload is documented in an IDDD. The IDDD is due at the HRCR. Included in the IDDD are the parts and materials list.

3.5.6 Payload Handling Requirements

A payload handling requirements list must be supplied prior to the delivery of flight units to the spacecraft integrator. This checklist describes any special handling necessary to ensure the safety of the flight hardware.

3.5.7 Unit History Log Book

The Unit History Log Book accompanies the delivery of the flight hardware.

3.5.8 Acceptance Data Package

The Acceptance Data Package includes, but is not limited to, final drawings, documents, mass properties, qualification data, footprint drawings, final power, etc.